Energy Saving Strategies on Mobile Devices

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Energy Saving Strategies on Mobile Devices

Ph.D. Thesis

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......dedicato ai miei genitori, alla mia famiglia e a tutte le persone che mi sono state vicine.

......to my parents, my family and everybody who supported me.

Abstract

Nowadays mobile phones of third generation (3G) are dominating the market of cellular communication systems. These phones have been provided with better hardware and are becoming more powerful day by day. Music and video players, in-built GPS receivers, high data rate for Internet connection, short range communication technology, high resolution cameras are just a few examples of what mobile phones can offer.
These new features changed mobile phones into so called smartphones, a very powerful platform allowing the creation of new services not limited to voice or Short Message Service (SMS) anymore. As a consequence, in the last years we have witnessed that new services were introduced such as Mobile Social Networks, Video Streaming, Location Base Services, Mobile VoIP, Multi Player Games, Mobile Banking and many more.
Since smartphones are battery driven, they have limitations in energy consumption. The energy limitation is related to the operational time, which is one of the most important issues for customers buying a new mobile handset. Therefore energy consumption in smartphones is very important for mobile manufactures, as the mobile device itself is more energy demanding and at the same time the customer asks for longer operational times. Currently, most smartphones are powered by lithium-ion batteries and at the moment the typical way to create more powerful batteries is to make them bigger. However this does not match well with the evolution of mobile terminals which tend to have less room available for the battery in order to accommodate additional components and technologies.
This PhD study introduces new strategies for using wireless data communication on mobile phones in a more efficient way, so that the energy consumption can be reduced and the operational time extended. The work can be divided in three main focus areas, namely *Cross Layer*, *Overlay Networks* and *Cooperation*.
In the first part of the thesis, Cross Layer concepts are used to reduce the energy consumption when considering a smartphone as a standalone entity.
The second area focuses on the Overlay Networks concept applied to Mobile Voice over IP where energy savings can be achieved if the information is routed

to the phone using the most energy efficient available network. Following this approach, energy consumption of a smartphone using VoIP services can be reduced significantly by using wake-up systems.

The third area investigates the energy saving potential of cooperation among mobile devices in proximity to each other by forming a cluster over their short-range technology. The cluster's members can share their cellular links to improve services like data steaming, file download and mobile web browsing.

This thesis includes five of the contributions belonging to the three aforementioned areas. Results show that the energy consumption of smartphones can be reduced and their battery life extended using the presented strategies. All results obtained are supported by a massive energy measurements campaign on commercial state of the art smartphones.

Resumé

I dag dominerer tredjegenerations "smartphones" markedet for mobiltelefoner. Disse smartphones bliver løbende udstyret med det nyeste hardware og bliver kraftigere for hver dag der går.
Musik- og videoafspillere, indbyggede GPS-modtagere, højhastighedsforbindelser til internet, nærkommunikation og højopløselige kameraer er bare nogle eksempler på hvad mobiltelefoner kan tilbyde.
Disse nye funktioner har gjort mobiltelefoner til såkaldte "smartphones", der udgør en meget kraftfuld platform der muliggør brugen af tjenester, som er langt mere avancerede end f.eks. SMS. Konsekvensen af dette er at vi gennem de seneste år har været vidne til introduktionen af nye tjenester som Mobile Sociale Netværk, Video Streaming, Lokaliseringsbaserede Tjenester, Mobilt VoIP, Spil med mulighed for flere deltager, Mobil Netbank og mange flere.
Idet smartphones er batteridrevne, er de pålagt en begrænsning i forhold til energiforbruget. Energibegrænsningen er relateret til hvor lange tid telefonen kan bruges mellem hver opladning, hvilket er et væsentligt kriterie når kunder vælger en ny mobiltelefon. Derfor vægtes energiforbruget højt af mobiltelefonproducenter, idet de mobile enheder i sig selv bruger mere strøm og kunderne efterspørger længere batterilevetid. I dag forsynes smartphones typisk af et lithium-ion batteri og p.t. forøges kapaciteten af disse primært ved at lave større batterier. Dog går dette imod udviklingen indenfor mobiltelefoner, hvor der typisk bliver mindre og mindre plads til batteriet idet de ekstra komponenter til understøttelse af nye funtioner som f.eks. kamera optager en større andel af den tilgængelige plads.
Arbejdet i denne Ph.D. introducerer nye strategier, der tilbyder en mere effektiv brug af trådløs datakommunikation in mobiltelefoner, hvilket reducerer energiforbruget og forlænger batterilevetiden. Arbejdet fokuserer på 3 hovedemner, forbedring på tværs af protokollag, overlejrede netværk og samarbejde.
I den første del af afhandlingen benyttes forbedringer på tværs af protokollag til at reducere energiforbruget når smartphone betragtes some selvstændige enheder.
Den anden del af afhandlingen fokuserer på at anvende overlejrede netværk i

forbindelse med Mobil Voice over IP, hvor energibesparelser kan opnås hvis informationen rutes igennem den telefon der har den mest energieffektive netværksforbindelse. Dette koncept medfører at energiforbruget i smartphones, der benytter VoIP-tjenester kan reduceres væsentligt ved brug af vækningsmetoder.
Under det tredje område undersøges potentielle energibesparelser ved samarbejde mellem mobile enheder der befinder sig tæt sammen ved at danne en klynge der anvender teknologier til nærkommunikation. Klyngens medlemmer kan dele deres cellulære forbindelse for at forbedre tjenester såsom streaming af video/lyd, hentning af filer og mobil web-browsing.
Denne afhandling inkluderer fem bidrag indenfor de tre ovennævnte områder. Resultaterne viser at smartphones' energiforbrug kan reduceres og deres batterilevetid kan forlænges med de præsenterede strategier. Alle opnåede resultater er understøttet af en massiv målekampagne af energiforbruget på kommercielle tidssvarende smartphones.

List of Publications

The thesis is based on the following papers:

PAPER A - An energy evaluation of Bluetooth Link Layer Packet adaptation. (G.P. Perrucci and M.V. Pedersen and T.K. Madsen and F.H.P. Fitzek), *Submitted to European Wireless '09*

PAPER B - On the Impact of 2G and 3G Network Usage for Mobile Phones' Battery Consumption. (G.P. Perrucci, F.H.P. Fitzek, G. Sasso, W. Kellerer, J. Widmer) *Submitted to European Wireless '09*

PAPER C - Using Wake-up Signals for Energy Savings in Mobile Devices (G.P. Perrucci, F.H.P. Fitzek, M.Katz) *In iC@ST magazine, volume 1, 2008.*

PAPER D - Energy Saving Aspects for Mobile Device Exploiting Heterogeneous Wireless Networks. (G.P. Perrucci, F.H.P. Fitzek, M.V. Petersen), *Heterogeneous Wireless Access Networks: Architectures and Protocols, Springer 2008.*

PAPER E - Cooperative Mobile Web Browsing (G.P. Perrucci, F.H.P. Fitzek, Q. Zhang, M. Katz), *Submitted to EURASIP Journal on Wireless Communications and Networking*

The following publications have been carried out by the author of this thesis during his Ph.D. studies.

Book chapters

- **G.P. Perrucci**, F.H.P. Fitzek, M.V. Petersen - Energy Saving Aspects for Mobile Device Exploiting Heterogeneous Wireless Networks. *Heterogeneous Wireless Access Networks: Architectures and Protocols, Springer 2008*

- **G.P. Perrucci**, A. Haber - Java 2 Micro Edition. *Mobile Phone Programming and its application to wireless networking, 2007.*

- J. Rasmussen, P. Østergaard, J. Jensen, A. Grauballe, **G.P. Perrucci**, B. Kryer, F.H.P. Fitzek - Parking Assistant Application. *Mobile Phone Programming and its application to wireless networking, 2007.*

- M. Pedersen, **G. Perrucci**, T. Arildsen, T. Madsen, F.H.P. Fitzek - Cross-Layer Example for Multimedia Services over Bluetooth. *Mobile Phone Programming and its application to wireless networking, 2007.*

Journals and magazines

- **G.P. Perrucci**, F.H.P. Fitzek, M.Katz - Using Wake-up Signals for Energy Savings in Mobile Devices. *In iC@ST magazine, volume 1, 2008.*

- **G.P. Perrucci**, F.H.P. Fitzek, Q. Zhang, M. Katz - Cooperative Mobile Web Browsing. *In EURASIP Journal on Wireless Communications and Networking* - SUBMITTED

- **G.P. Perrucci**, P. Anggraeni, S. Wardana, F.H.P. Fitzek, M. Katz - Bio-Inspired Energy-Aware Medium Access Control Protocol for Cooperative Wireless Networks. *In International Journal of Autonomous and Adaptive Communications Systems* - SUBMITTED

Conference papers

- **G.P. Perrucci**, F.H.P. Fitzek, G. Sasso, M. Katz - Energy saving strategies for mobile devices using wake-up signals. *In MobiMedia - 4th International Mobile Multimedia Communications Conference Oulu - Finland, 2008.*

- **G.P. Perrucci**, P. Anggraeni, S. Wardana, F.H.P. Fitzek, M. Katz - Bio-inspired Energy-aware Medium Access Control Protocol for Cooperative Wireless Networks. *In Workshop on Bio-inspired Wireless Networks in conjunction with 2008 International Symposium on Performance Evaluation of Computer and Telecommunication Systems Edinburgh - UK, 2008.*

- **G.P. Perrucci**, F.H.P. Fitzek, A. Boudali, M. Canovas Mateos, P. Nejsum, S. Studstrup - Cooperative Web Browsing for Mobile Phones. *In International Symposium on Wireless Personal Multimedia Communications WPMC'07. Jaipur - India, 2007.*

- **G.P. Perrucci** and M.V. Pedersen and T.K. Madsen and F.H.P. Fitzek - An energy evaluation of Bluetooth Link Layer Packet adaptation. *In European Wireless '09* - SUBMITTED

- **G.P. Perrucci**, F.H.P. Fitzek, G. Sasso, W. Kellerer, J. Widmer - On the Impact of 2G and 3G Network Usage for Mobile Phones' Battery Consumption. *In European Wireless '09* - SUBMITTED

- C. Sammarco, F.H.P. Fitzek, **G.P. Perrucci**, A. Iera, A. Molinaro - Localization Information Retrieval Exploiting Cooperation Among Mobile Devices. *In IEEE International Conference on Communications IEEE International Conference on Communications, ICC 2008 - CoCoNet Workshop Beijing - China, 2008.*

- T.K. Madsen, F.H.P. Fitzek, **G.P. Perrucci**, T. Andrilsen, S. Nethi - Novel IP Header Compression Technique for Wireless Technologies with Fixed Link Layer Packet Types. *In GLOBECOM, 2006.*

- M.V. Petersen, **G.P. Perrucci**, F.H.P. Fitzek - Energy and Link Measurements for Mobile Phones using IEEE802.11b/g. *In The 4th International Workshop on Wireless Network Measurements WiNMEE 2008 - in conjunction with WiOpt 2008. Berlin - Germany, 2008.*

- K. Revsbech, J. Heide K.H. Hansen, **G.P.Perrucci**, F.H.P.Fitzek - Energy Saving Potential Using Active Networking on Linux Mobile Phones. *In IEEE International Conference on Communications, ICC '09* - SUBMITTED

- A. Grauballe, **G.P. Perrucci**, F.H.P. Fitzek - Introducing Contextual Information to Mobile Phones by External and Embedded Sensors. *In International Workshop on Mobile Device and Urban Sensing - MODUS08. St. Louis Missouri USA, 2008.*

- A. Grauballe, **G.P. Perrucci**, F.H.P. Fitzek - Opensensor - An open wireless sensor platform. *In MobiMedia - 4th International Mobile Multimedia Communications Conference Oulu - Finland, 2008.*

- Della Rosa F., Simone G., Laurent P., Charaffedine R., Mahmood N. H., Pietrarca B., Kyritsi P., Marchetti N., **Perrucci G.P.**, Figueiras J., Frattasi S. - Emerging Directions in Wireless Location : Vista from the

COMET Project - INVITED. *In Proceedings of the 16th IST Mobile and Wireless Communications SummitIEEE, 2007.*

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- F.H.P. Fitzek, M.V. Pedersen, **G.P. Perrucci**, S. Rein, C. Ghmann - Convergence of Mobile Devices and Wireless Sensor Networks. *In Wireless World Research Forum. WWRF. Heidelberg Germany, 2006.*

- T.K. Madsen, F.H.P. Fitzek, **G.P. Perrucci**, R. Prasad - Joint Approach for IP Overhead Reduction in Wireless Ad Hoc Networks. *In International Symposium on Wireless Personal Multimedia Communications. WPMC San Diego CA - USA, 2006.*

- F.H.P. Fitzek, S. Rein, M.V. Pedersen, **G.P. Perrucci**, T. Schneider, C. Ghmann - Low Complex and Power Efficient Text Compressor for Cellular and Sensor Networks. *In IST Mobile Summit. Mykonos - Greece, 2006.*

Preface

This thesis is submitted to the Faculty of Engineering, Science and Medicine at Aalborg University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The work was carried out during the period February 2006 - January 2009 at the Department of Electronic Systems at Aalborg University and financed by the X3MP project granted by Danish Ministry of Science, Technology and Innovation.

I would like to take this opportunity to thank my main advisor Frank H.P. Fitzek for providing me with the freedom to pursue my interests, for believing in my abilities and for his valuable technical support. I would also like to thank my co-advisor Tatiana K. Madsen for her support in the last three years. I have greatly benefited from the technical knowledge of both of them and their motivation has been very useful for me during my study.

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Contents

Introduction

The idea of communicating in a mobile manner is many years old, but it took decades to make it possible and even more to make it appealing for the mass market. The first radiotelephones were available in the '20, while in the '30 the two-way radios for police cars, ambulances, and taxis were available. Even though these communication systems were mobile, they were very limited for two main reasons. Firstly, their range was short, and secondly they could only enable communication between fellow users, not with all telephone subscribers [1]. The last three decades saw a revolution thank to the improvement of mobile networks and terminals, which allowed the communication to become totally mobile and on global basis. Figure 1 shows some pictures of mobile phones as a time scale of the evolution of terminals in the last years. In the end of the '70 the first

Figure 1: Mobile phones' evolution.

generation of commercial phones was available for the mass market. They could be only used for establishing voice calls and they were bulky and heavy.
With the second generation (2G), mobile phones increased their functionalities and services thank to the Short Messaging Service (SMS) and later the first data connections based on the Wireless Application Protocol (WAP). At the

same time the design started to become more appealing for users and terminals started to be equipped with larger resolution and color displays. Due to the drop of terminals prices and communication fares, mobile phones quickly increased their popularity and quickly became a symbol of fashion and status, specially among the youngsters.
During the last decade the third generation of mobile phones has dominated the market [2, 3] and because of the remarkable increase in functionalities, mobile phones started to be called smartphones.
In fact the computing technology is developing according to the Moore's law which states that the number of transistors that can be inexpensively placed on an integrated circuit is doubling every 18 months[1] [4]. As a consequence, smartphones have been provided with better hardware and are becoming more powerful day after day.
All smartphones on the market are nowadays equipped with audio and video players, FM radio, photocameras with resolutions up to eight megapixels, able to shoot photos as well as video in different formats. Additionally they offer several technologies for data communications both over the cellular link [5, 6] (GPRS, EDGE, UMTS, HSDPA) and over short range (Bluetooth, WLAN 802.11b/g, Near Field Communication) [7, 8, 9, 10]. Other features include in-built GPS receivers, large touch screen displays, QWERTY keyboards and memory for data storing up to 32 GB.
Exploiting the new available technologies, new services have been created for mobile users. Some of them are just evolution of existing ones, such as Video Call Service (the evolution of the traditional voice service) and Multimedia Messaging Service (MMS, the evolution of the SMS) [11], but many others are brand new. Mobile banking, mobile blogging, mobile social networking, Mobile Peer-to-Peer, Location Based Services, Mobile video steaming, Mobile Web Browsing, Mobile VoIP are just some examples of popular services available at the moment.
Along with the creation of new services, several applications for smartphones have been developed to access these services. Some examples are *Fring* [12] (a mobile client for VoIP with plugins for managing Facebook, Skype, MSN and other online communities), *ebuddy* [13] (a mobile web messenger to interact with MSN, Yahoo, Google Talk, MySpace and AIM communities), *Symtorrent* [14] (a mobile BitTorrent client), *Aka Aki* [15] (mobile social network application), *The journey* [16] (a mobile location based game), Loopt [17] (a location based mobile social network), Google maps for mobile [18], Youtube for mobile [19] and the number of applications is increasing rapidly.

[1] Later Moore corrected this value from 18 to 24 months

1 Problem definition

As mentioned before, mobile phones have been undergoing a breathtaking evolution over the years, starting from simple mobile phones with only voice services towards the transition of smartphones offering several kind of services. Terminals are battery driven to allow the highest degree of freedom for the user and therefore they have limited resources in terms of energy and power. It is crucial to understand the difference between these two terms that sometimes are used interchangeably.

Power: the rate at which work is performed $\Rightarrow Power = Work/Time\ [Watts]$

Energy: the time integral of Power $\Rightarrow Energy = Power * Time\ [Joules]$

Power and energy play some key roles in the evolution of smartphones as the improvement of battery capacity is quite moderate [20] compared to the increase of the complexity due to new hardware and services.
Since the battery stores a fixed amount of energy, the operational time the user is able to use its phone within one charging cycle, namely *battery life*, is fixed as well. As smartphones are offering more and more energy hungry features and services, battery life gets shorter.
To overcome this problem, energy consumption needs to be reduced. In some cases reducing the power consumption is sufficient to reduce the energy consumption as well. This is true for tasks with a constant duration (i.e. video and audio playing, voice calls) because the energy spent is proportional to the average power consumption.
On the other hand, some other tasks will require less energy if performed faster but with high power rather than slower with a low power consumption [20]. An example is data downloading and uploading. However using high power, even for a short time, has a limit due to the *heating* of the mobile phone.
Therefore, it is crucial to reduce the energy consumption in order to allow the evolution of smartphones, though often it is not that trivial. In the following section, issues related to *battery life* and *heating* of the phone are discussed.

1.1 Battery life

As services are the main distinction among mobile devices from different vendors, the manufacturer will always use the fully available computational power to develop new services. As shown in Figure 2 more features and services a smartphone offers, larger the energy consumption can be.
This increase in energy consumption results in lower operational times for the users, also referred as stand-by time. As the stand-by time has become one important purchase criteria, energy saving strategies are becoming more and

Figure 2: Increasing services and features on smartphones leads to a larger energy consumption.

more important. This is not only a problem for users, but for mobile service providers as well. If the phone runs out of battery, users cannot access mobile services any longer, reducing the revenues of providers. Therefore mobile phone manufacturers are very keen in developing solutions to extend the battery life.
Using batteries with more capacity could be a trivial solution, but unfortunately their technological evolution does not follow the trends dictated by Moore's law. While the computational complexity is doubled every two years according to Moore, the battery capacity is doubling only every decade.
In the current state of the art, most smartphones are powered by lithium-ion batteries [21]. These batteries are popular because they can offer many times the energy of other types of batteries in a fraction of the space.
At the moment, engineers cannot sufficiently increase the amount of energy created by the chemical reactions and the only way to create more powerful batteries seems to be making them larger. However this does not well match with the evolution of mobile terminals which tend to have less room available for the battery in order to accommodate additional components and technologies.
There are some new trends though. Some researchers at Stanford university are using nanotechnology [22] to make batteries able to produce 10 times the

amount of electricity of existing lithium-ion batteries. Other researchers try to exploit the movement of the user to recharge the battery [23]. But these are only initial research fields.

1.2 Heating

All the applications and mobile services mentioned in the introduction require a large amount of data to be exchanged. Even though high data rates are already available on the smartphones' platform, applications using wireless air interfaces have an high power consumption as shown in Figure 1. Naturally, the enormous

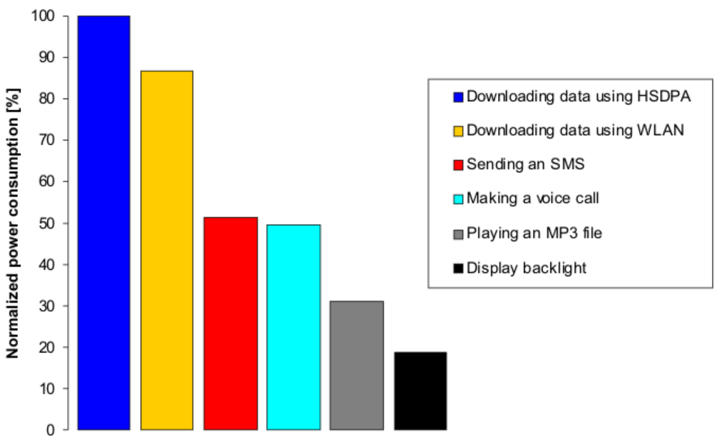

Figure 3: Power consumption for different phone's services normalized to the power consumption needed for downloading data using HSDPA. Measurements taken on a Nokia N95 smartphone.

power consumption leads to heating problems. To illustrate the problem of heating, in Figure 4 some pictures of a Nokia N95 taken with a thermal camera are shown. The pictures have been taken with a time interval of three minutes while the phone is downloading data using HSDPA and WLAN simultaneously and at the same time trying to get the GPS position. The light of the display was turned off. This sequence of pictures shows that the temperature of the device increases with the time and the maximum temperature reached is in the range of 45° Celsius when the plastic cover of the battery is removed (the two pictures in the bottom). In this example the phone was accessing only few of the available services simultaneously, but in real life a user could stress the phone even more.

Therefore, if the complexity keeps on increasing, soon smartphones will not be

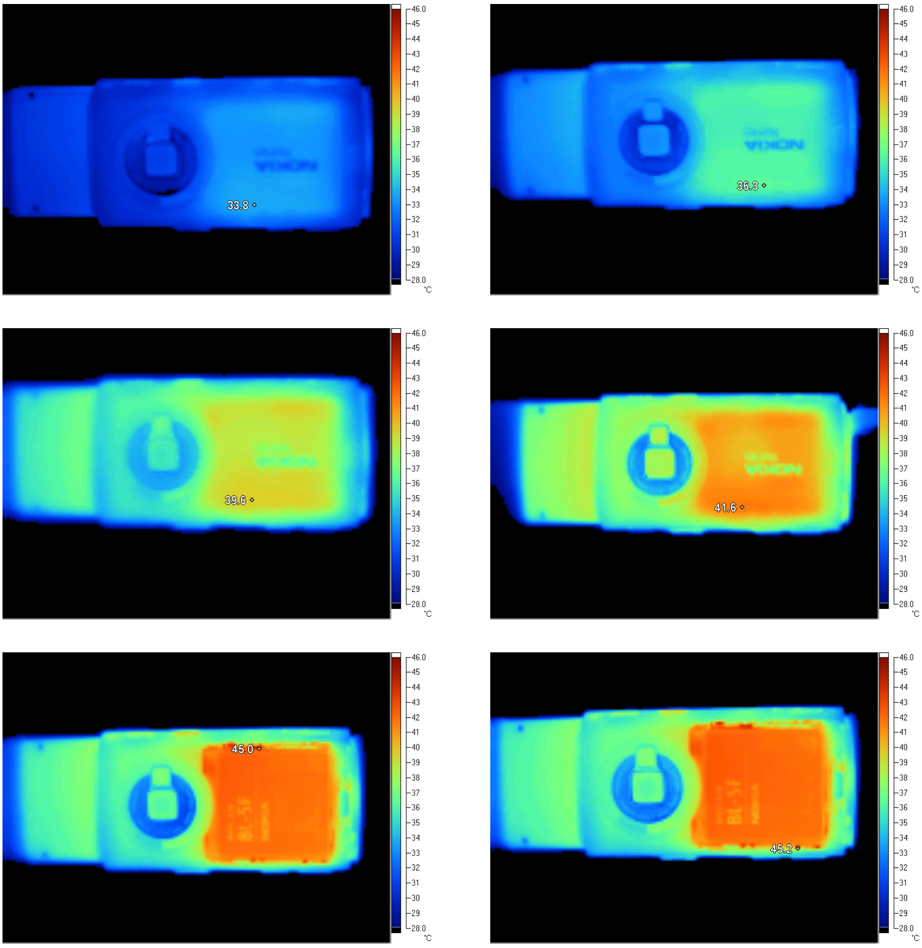

Figure 4: Thermal pictures of a Nokia N95 downloading data using HSDPA and WLAN simultaneously and at the same time trying to get the GPS position. The pictures have been taken with an interval of three minutes between each one. The sequence shows the increase of heat over the time while the phone is performing the aforementioned actions.

able to cope with the heat, making passive cooling unfeasible and active cooling will surely be necessary.

2 Contribution

As the upcoming fourth generation (4G) smartphones will be even more complex than 3G ones, the question arises how the battery should cope with this new challenge. The increase in energy consumption of mobile phones is the reason

Figure 5: A public mobile phones' charger, a device becoming very popular in airports, hotel and conference centers.

why public battery chargers at airport and hotels are getting more popular. Those public chargers have several cable plugs for different mobile phone models (see Figure 5), offering a solution to charge the phone on the go.

As this is clearly not a convenient solution, the main objective of this PhD work is to study new strategies for using wireless data communication on mobile phones in a more efficient way, so that the energy consumption can be reduced and the battery life extended. Figure 6 shows the three main areas where new strategies have been identified and studied. These strategies can be applied to a stand-alone terminal (using the *Cross Layer* approach), to a stand-alone terminal having access to different kind of networks (using the *Overlay Networks* concept) and finally to a group of smartphones forming a cooperative cluster (using *Cooperation*).

This thesis includes some of the contributions in the three aforementioned areas

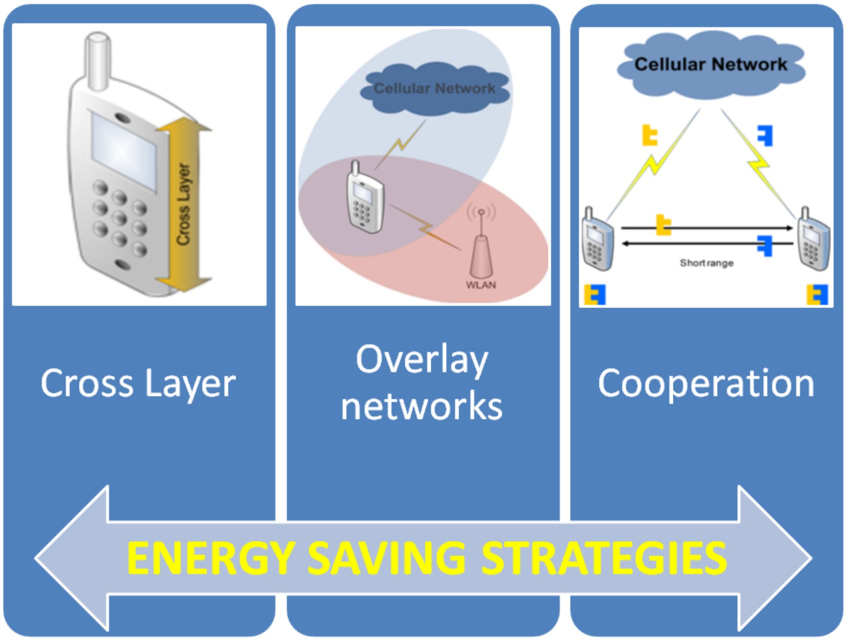

Figure 6: This picture shows the three main areas that have been studied for validating energy saving strategies, namely *Cross Layer*, *Overlay Networks*, *Cooperation*.

and in the following a summary of all of them is given.
For details such as co-authors and publication data, see the individual papers. Moreover, a complete list of publications carried out during my PhD studies can be seen at page *iii*.

2.1 Cross Layer

Cross Layer protocol design [24, 25] can be used to improve performance of layered protocol stacks (i.e. ISO-OSI model [26]) by allowing communication between non-adjacent layers. In *PAPER A* and *PAPER B* we use the Cross Layer concept to change directly from the *Application Layer* some parameters of lower layers (i.e. Bluetooth packet types and network connection type respectively).

PAPER A: This paper investigates the energy saving potential of Bluetooth. When using the asynchronous connectionless link (ACL) for data transmission, Bluetooth provides different packet types, namely DM and DH packets. Each packet has a different payload size and in the actual implementation the packet selection is based on the channel conditions. Measurements done on commercial smartphones show that energy savings are achieved by selecting the appropriate packet type in an energy aware manner. In fact, by forcing the phone to use a specific packet type, results prove that the energy consumption can be reduced up to 40% depending on the payload size.

PAPER B: This paper presents results of power and energy consumption measurements conducted on mobile phones for 2G and 3G networks. The services under investigation are text messaging, voice and data download. The paper reports a larger energy consumption in 3G networks than in 2G networks for text messaging and voice services. On the other hand 3G networks become more energy friendly when large volumes of data have to be downloaded. Results imply that mobile phones should switch the network in dependency of the service to use in order to save the maximum amount of energy. This intelligent switching in the studied scenario can lead to energy savings in the range of 45%, 18% and 75% for voice, SMS and data downloading respectively.

2.2 Overlay Networks

As provided with several air interfaces, smartphones can be connected to different networks (Cellular, WLAN and Bluetooth, Near Field Communication) at the same time. Therefore energy savings can be achieved if the information is routed to the phone using the most energy efficient network. This is the case studied in *PAPER C*, where the so called Overlay Networks concept is applied to Mobile Voice-over-IP (VoIP).

PAPER C: This paper investigates the use of wakeup signals for Mobile VoIP. WLAN chip-sets are becoming more common on smart phones, allowing users to use VoIP services from their mobile devices. On the other hand, the excessive energy consumption of the WLAN chip-set, limits the widespread use of mobile VoIP. As most of the energy is spent when the WLAN is in idle mode waiting for a call, a possible solution is to use a secondary air interface (more energy efficient, i.e., GSM or Bluetooth), as a signaling channel to wake up the WLAN radio upon incoming call events. Two different ways of implementing such a wake-up system have been presented, namely *overlay* and *cooperative* approach. Analytical results have been supported by measurements of energy consumption on an commercial device (Nokia N95). Finally four different user cases have been analyzed for the overlay approach showing that wake-up systems can reduce significantly the energy consumption of a mobile phone for VoIP services when compared to the conventional approach. It has been shown that the overall gain of the proposed approaches depends heavily on the users' call activity. Nevertheless, for a broad range of user call activities a clear gain by the different approaches has been demonstrated.

2.3 Cooperation

In the actual state of the art, cellular communication systems are characterized by the communication between a base station and mobile terminals. The idea behind Cooperation [27, 28, 29, 30] is to enable an extra communication link between smartphones within a short range proximity for example using Bluetooth or IEEE 802.11b/g [31, 32, 33]. In *PAPER D* and *PAPER E* energy consumption and performance of services (i.e. *file download*, *streaming*, *web browsing*) based on Cooperation are evaluated.

PAPER D: In this book chapter an analytical derivation of the energy consumption of cooperative wireless networks compared to non cooperative state of the art ones is given. The main focus is on the energy consumption and delay behavior for such an architecture. Potential gains for cooperative wireless networking are presented by using results of measurements on commercially available mobile phones in the analytical derivations. For two different scenarios it is shown that cooperative wireless networking with existing heterogeneous wireless technologies, such as 3G, IEEE802.11 b/g, and Bluetooth, can already offer large energy savings and delay reduction for the *file download* scenario. For the *streaming* scenario, the gains are small in case of Bluetooth or not existing in case of WLAN.

PAPER E: This paper advocates a novel approach for mobile web browsing based on cooperation among wireless devices within close proximity operating in a cellular environment. In the actual state of the art, mobile phones can access the Web using different cellular technologies. However, the supported data rates are not sufficient to cope with the ever increasing traffic requirements resulting from advanced and rich content services. By using the concept of cooperative networks, smartphones can be grouped together in clusters, using a short-range communication such as Bluetooth, sharing and accumulating their cellular capacity. The accumulated data rate resulting from collaborative interactions over short-range links can then be used for cooperative mobile web browsing. Results show that cooperative web browsing by two mobile devices can increase the virtual capacity of the cellular link and can thereby reduce the duration of the downloading time. Therefore this new architecture can be used to overcome the problem of low data rates for Internet access on mobile phones. On the other hand, results show that energy consumption slightly increases when using the cooperative web browsing. Nevertheless, to achieve the same performance in terms of datarate, a non cooperating standalone mobile phone would even pay an higher price in terms of complexity and energy as well.

Conclusion

The evolution of mobile phones in the last decade has been remarkable. In less than ten years mobile phones starting with voice services and text messaging, became multimedia devices. The increasing number of energy hungry features and services on the smartphones' platform has led to a reduction of operational time due to the exhaustive energy consumption. Smartphones are battery driven and the improvement of battery capacity is quite moderate if compared to the dramatically increase of the complexity of the terminals. Therefore energy consumption represents a bottleneck for the evolution of such devices and it needs to be reduced.

In this PhD work new strategies for using wireless communication on smartphones in a more energy efficient way are proposed and discussed. The contributions of this PhD study falls in three main focus areas, namely *Cross Layer*, *Overlay Networks* and *Cooperation*.

Regarding the first area, Cross Layer concepts have been used to reduce the energy consumption when considering a smartphone as a standalone entity. Results show that by changing directly from the *Application Layer* some parameters in the lower layers, energy savings are possible. For example by forcing the phone to use a specific Bluetooth packet type (when using the asynchronous connectionless link for data transmission), the energy consumption can be reduced up to 40% depending on the payload size (*PAPER A*). Moreover, in *PAPER B* results show that by switching the type of network connection in dependency of the service to use, energy savings in the range of 45%, 18% and 75% are possible for voice, SMS and data downloading respectively.

The second area focuses on the Overlay Networks concept applied to Mobile Voice-over-IP where energy savings can be achieved if the information is routed to the phone using the most energy efficient available network. *PAPER C* introduces the use of wake-up signals for Mobile VoIP. Results show that wake-up systems can reduce significantly the energy consumption of a smartphone using VoIP services.

The third area studies the use of Cooperation to improve services, such as data steaming, file download and mobile web browsing. The cooperation approach

envisions mobile phones in proximity of each other to form a cluster using their short-range technology and share their cellular links. An analytical derivation of the energy consumption of cooperative clusters supported by results of measurements on commercially available mobile phones is given in *PAPER D*. Results show that cooperative wireless networking with existing heterogeneous wireless technologies, such as 3G, IEEE802.11, and Bluetooth, can already offer large energy savings and delay reduction. In *PAPER E* we have presented the cooperative web browsing idea that can be used to overcome the problem of low data rates for Internet access on mobile phones. Even if results show that energy consumption slightly increases when using the cooperative web browsing, a non cooperating standalone smartphone would pay an higher price in terms of complexity and energy to achieve the same speed performance.
All results presented in the collection of papers enclosed in this thesis are supported by a massive energy measurements campaign on commercial state of the art smartphones.

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Paper A

An Energy Evaluation of Bluetooth Link Layer Packet Adaptation

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Abstract

This paper is investigating the energy saving potential of Bluetooth. Using the asynchronous connectionless link (ACL) for data transmission, Bluetooth provides different packet types, namely DM and DH packets. Each packet has a different payload size and in the actual implementation the packet selection is based on the channel conditions. In this paper we present and discuss results of a measurements campaign that we have made on commercial mobile phones. We show that energy savings can be achieved by selecting the appropriate packet type in an energy aware manner, by forcing the phone to use a specific packet type.

1 Introduction

Mobile communication is based on wireless devices that are using batteries to allow the highest possible degree of freedom for the user. As mobile devices are crammed with all possible services nowadays the energy consumption of those mobile devices has been increased over the last decades and will keep on increasing dramatically.
Multimedia services, for example, are one of the most important keys for the success of next generation of mobile phones. Many companies are focusing their attention on making applications for the delivery of multimedia contents, in order to provide mobile users with services as they have on their PC. However, this kind of applications require a large amount of data to be exchanged, therefore a larger bandwidth than traditional voice services. High data rates are already available for mobile phones thanks to different technologies: WLAN, Bluetooth, UMTS and HSDPA, but the energy required when transferring data is remarkable.
The energy consumption is not following Moore's law. Even though Moore's law is referring to the computational power, that is doubling every two years, the computational power will be used to create new services on mobile devices. As services are the main distinction among mobile devices from different manufactures, the manufacturer will always use the fully available computational power. Larger energy consumption is resulting in lower operational times for the users, also referred to as stand-by time. As the stand-by time has become one important purchase criteria, energy saving strategies are becoming more and more important.

2 Motivation

Following the aforementioned introduction, this paper is looking into energy saving potential for Bluetooth communications. In contrast to the majority of mobile communication systems in the area of wireless local area networks (WLANs), Bluetooth has several types of communication packets with fixed lengths. E.g. IEEE802.11 is using packets with variable lengths (with a minimum and maximum limitation). According to the standard, Bluetooth provides duplex transmission based on Time-Division Duplexing (TDD) where the duration of each slot is fixed to 625 μs.
Between two or more Bluetooth devices, two types of links for data transmission can be established:

- Synchronous Connection Oriented link (SCO)
- Asynchronous Connectionless link (ACL)

For the ACL data transmission, Bluetooth provides different packet types which are classified in DM and DH packets. The latter ones are using the full packet space to convey higher payload, while the first type is reserving some part of the packet for a 2/3 Forward Error Correction (FEC) scheme: for every 10 bytes of packet data 5 bytes of error correcting code are added. The initial intention of the Bluetooth standard was that DM packets are less prone to errors on the unreliable wireless link. DM packets can carry less bits than DH packet due to the additional FEC information. Each sent packet is acknowledged in the following time slot. As this is quite inefficient if the acknowledging peer has nothing to send back, Bluetooth has the possibility to accumulate time slots for the sending device. It is possible to aggregate three or five slots, which are acknowledged only by one time slot as shown in Figure 1. Thus, with different packet types and aggregation factors, there are six possible Bluetooth packets that can be used for transmission. These different packet types should provide a good trade off

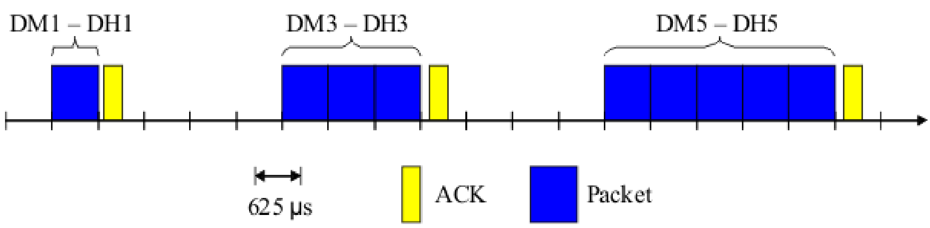

Figure 1: Time slots in ACL communication

between robustness and throughput. For example DM packets provide a high

Table 1: Bluetooth packet type.

Packet Type	Duration (slots)	Payload (Bytes)	FEC
DM1	1	17	YES
DH1	1	27	NO
DM3	3	121	YES
DH3	3	183	NO
DM5	5	224	YES
DH5	5	339	NO

robustness but a very low throughput, whereas DH packets provide a higher throughput reducing the robustness. In Table 1 the different packet types with the related payload information length are given [4]. For further information about Bluetooth we refer the interested reader to the Bluetooth SIG (Special Interest Group) website [1], where the complete specification for the different Bluetooth versions can be found.

In this paper we investigate the performance of the different packet type selection in terms of energy. Previous works on the effects of Bluetooth packet type selection include [3], in which authors propose an analytical method to determine the optimal packet type for a given channel state to improve the TCP throughput. In [9] authors present a method to choose the optimal packet type in order to maximize the throughput efficiency of the ARQ protocol based on the acknowledgement history of the most transmitted packets. In [5] and [8] authors investigate the advantages of choosing a specific packet type to make possible the stream of high-quality videos over Bluetooth and the throughput dependence on packet type in a Bluetooth network interfered by other devices, respectively.

Differently from the aforementioned works where results have been carried out by simulations, we have conducted a measurement campaign on commercial mobile phones to evaluate the performance for Bluetooth communication using different packet types. This is the first work of this kind according to our best knowledge and results are presented in the Section 4.

3 Measurement Setup

We have used two different models of phones for the measurements, namely Nokia N95 an Nokia N71. The N95 is running Symbian OS v9.2 as operating system and is using a Bluetooth 2.0+EDR chipset whereas the N71 is running Symbian OS v9.1 and a Bluetooth 1.2 chipset. The setup includes also an AGI-

LENT 66319D used as multimeter as shown in Figure 2. The Agilent machine

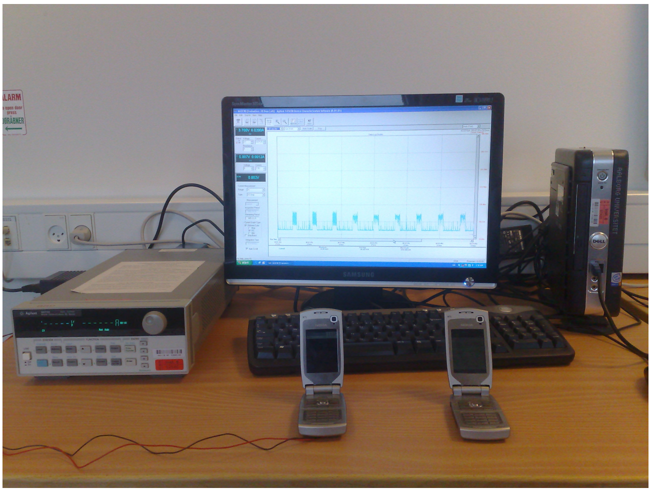

Figure 2: Setup for the measurements. Two N71s running our application and the sender (on the left) is connected to the AGILENT 66319D.

is connected to a PC which is running the Agilent 14565B device characterization software, a tool designed for evaluation of portable battery powered device current profiles.

We have developed an application which forces the phone to use a preselected packet type when transmitting data. We used Python for S60 [6], [7] as programming language to develop scripts for testing, but because of lack of needed APIs, we have written an extension module in Symbian C++ to choose specific Bluetooth packet types for data transmission.

The aim of the measurement campaign is to find out the power consumption, the time (and therefore the energy) needed for data transmission using different packet types and data payload sizes. Let us note that the sender phone is connected to the AGILENT 66319D to measure the power consumption and log it into a file. When the N95 is used as a sender, the in-built energy profiler [2] developed by Nokia is used as well. The Nokia Energy Profiler is an software running on the mobile device that measures consumptions of the phone, such as power, current, network usage and so on. This helped us in validating the obtained results.

The first step of each measurement consists of establishing a Bluetooth connection between the two phones. The sender and receiver are standing 10 cm apart from each other.

Upon a successful connection, the testing starts. Each test consist of transmitting a certain amount of data (D), using one specific Bluetooth packet type (PT) for 3000 times (N_{trans}) and it is repeated for all the possible combinations of D (from 1 up to 350 bytes) and PT: DM1, DH1, DM3, DH3, DM5, DH5, and auto (letting the phone decide which packet type to use). During the tests a log file is created on the sender phone to keep track of the time spent for completing the test. We calculated the value of power consumption per test as the mean value of all the samples obtained by the AGILENT 66319D during each time interval. We repeated all the measurements 10 times using always one N71 as receiver and as sender alternatively a N71 or an N95 was used. Finally we obtained values for time duration and power consumption by averaging the values of each repetition. Therefore we calculated the energy spent by multiplying the time and the power consumption.

4 Results and discussion

In this section we only present the results of measurements of time and energy consumption on the Nokia N95 used as sender because of space limitation. Nevertheless, we want to mention here that when using the Nokia N71 as sender we obtained similar results regarding the time. In terms of energy we have measured a consumption around 30% smaller than the N95. However this difference can be due either to the different Bluetooth chipsets used or to the different processing power needed by the phone itself, but unfortunately we are not able to be more precise about this fact as we are unable to separate the two consumptions.
In order to compare the measurements with the ideal case, we need to calculate the time for data transmission using different packet types without considering retransmissions. Given a certain payload, the ideal time T_{Ideal} can be calculated using the Equation 1:

$$T_{Ideal} = N_{trans} * (0.000625s * (N_{slots} + 1)) * N_{Packets}, \quad (1)$$

where N_{trans} is the number of transmissions, N_{slots} is the number of time slots used depending on the packet type (see Figure 1) and $N_{packets}$ is the number of packets needed to transmit a given amount of data (see Table 1). Measurements of time needed for sending 3000 times a chunk of data from 1 to 350 bytes length using different packet types is shown in Figure 3. Since we cannot access some restricted information of the Bluetooth implementation on the devices, we treat the phone as a black box. We can understand how it works only by observing its behavior and making measurements. In fact, the actual implementation of Bluetooth it is up to the phone's and chipset's manufacturers and sometimes it can slightly differ from the standard specification.
As a proof, in the following we compare the measurements of transmissions using different packet types to the ideal case. Results show that there is a mismatch

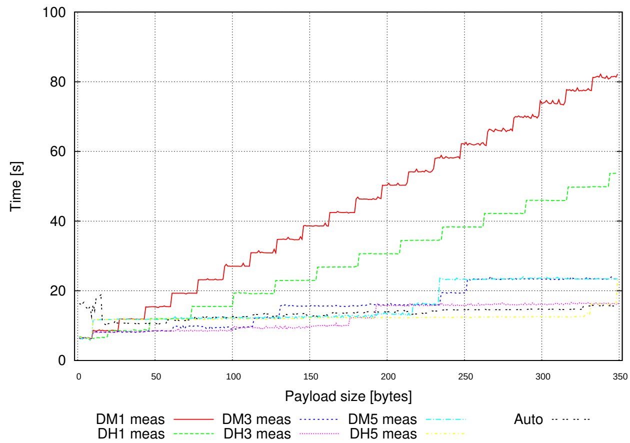

Figure 3: Time needed for 3000 transmissions using all the packet types for payload varying from 1 to 350 bytes.

between the ideal curves and the measured ones. First of all, because of retransmissions, the time measured is always larger than the ideal one, as can be observed looking at Figure 4.

Secondly, and most importantly, the curves of the measured time have an offset of 8 bytes compared to the ideal one. Our guess is that 8 bytes extra are transmitted in addition to the actual payload as we explain in the following.

For DM1 packets the maximum payload according to the specifications is 17 bytes. In fact the ideal curve has a jump in time duration when the payload is a multiple of 17 bytes and therefore two packets need to be transmitted. Although as shown in Figure 4, the first jump happens at 9 bytes of payload and then is repeated every 17 bytes. This proves our theory according to which 8 extra bytes are transmitted. The same behavior is visible in Figure 5 for DH1 packets, where the jump should be at 27 bytes, whereas in the measurements it happens at 19 bytes. Something more interesting happens when using 3-slots and 5-slots packets. From the plots it seems that transmitting a packet with a payload smaller or equal to 9 bytes, is faster than the ideal case. This strange behavior brings us to think that the first packet sent out, is always a DM1 packet. This contains 8 extra bytes plus the payload. Once it is full, the 3-slots or 5-slots packet is used. For example in Figure 6, when the payload size is smaller or equal to 9 bytes, a DM1 packet is used. Then from 10 to 113 bytes, one DM3 packet is used. From 114 to 130 bytes one DM1 for the first 27 bytes (8 extra plus 19 of payload) and one DM3 packet for the rest of the payload is used. From 131 to 234 bytes two DM3 packets are transmitted. From 235 to 251 bytes, one

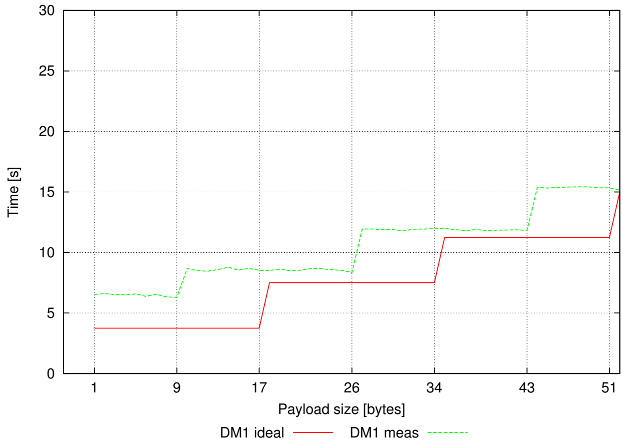

Figure 4: Time needed for 3000 transmissions using DM1 packets.

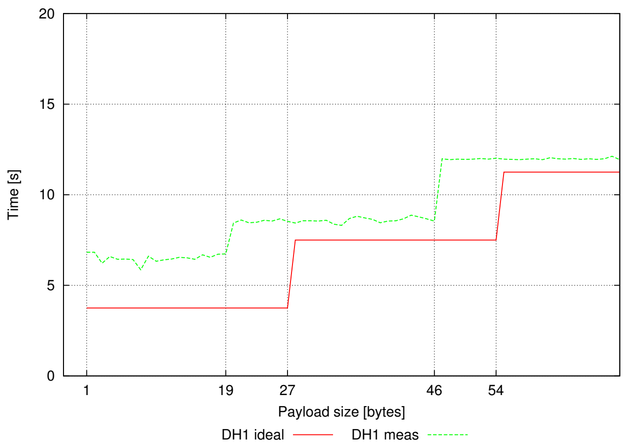

Figure 5: Time needed for 3000 transmissions using DH1 packets.

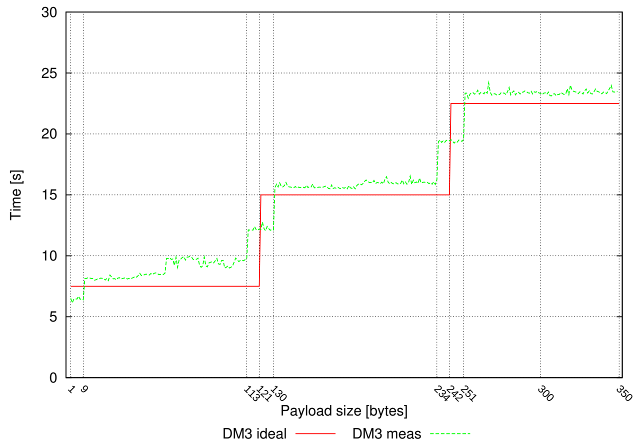

Figure 6: Time needed for 3000 transmissions using DM3 packets.

DM1 and two DM3 packets are transmitted and so on. A similar behavior can be found in Figure 7, Figure 8 and Figure 9 for DH3, DM5 and DH5 packets respectively. Having understood the behavior in time of the use of different packet types, we focus our attention on the energy consumption. We want to compare the energy spent when we force the phone to use a specified packet type to the energy spent when the phone makes the selection itself. In Figure 10 the traces of the energy consumption for all the different packet types and the auto selection are shown. Table 2 reports the packet types less energy consuming than the automatic selection in the second column and the one which has the least consumption among all the types in the third column for different intervals of payload sizes. DH3 packets seem to be the most energy efficient choice for payload size from one up to 192 bytes. From 193 to 331 bytes, DH5 performs better than all the others and finally the auto selection is the best choice for payload size from 332 to 350 bytes.

Results show that DM packets, in the studied scenario, are less energy efficient than DH ones, therefore having an FEC scheme does not pay off. In fact DM packets are protected by a 2/3 FEC scheme that allows 1 in 15 bytes to be corrupted but have less payload sizes. When using DH packets any single byte error would cause the packet to be discarded. However in the real world, errors happen mostly when we are on the limits of the range and therefore when the transmission takes place within a short range FEC becomes insignificant. To show the effect of errors when increasing the distance between the two phones, we have made some extra tests transmitting 3000 times a packet with 110 bytes

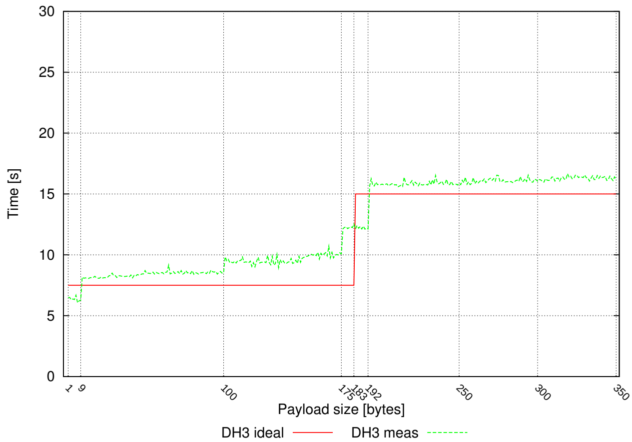

Figure 7: Time needed for 3000 transmissions using DH3 packets.

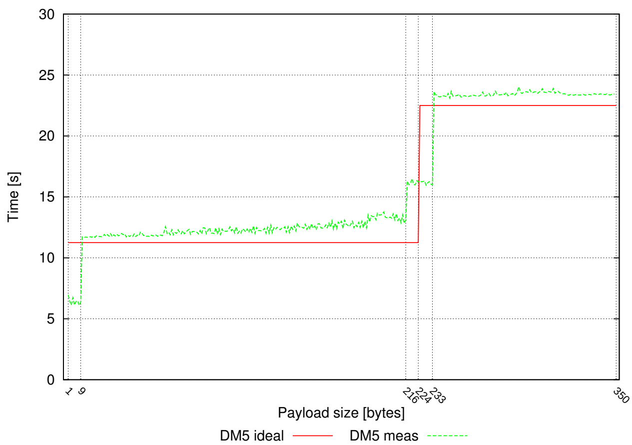

Figure 8: Time needed for 3000 transmissions using DM5 packets.

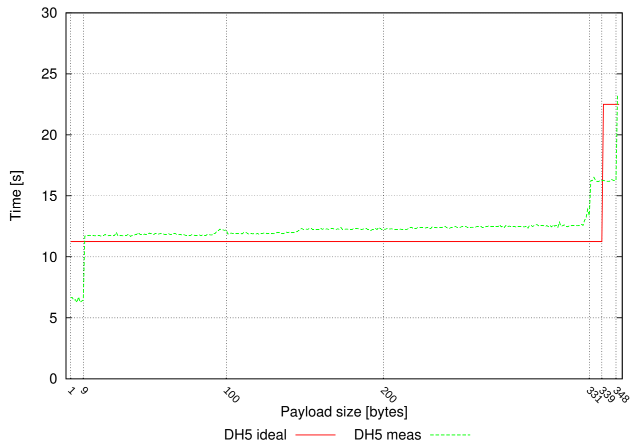

Figure 9: Time needed for 3000 transmissions using DH5 packets.

Table 2: Energy consumption

Payload	**Less than auto selection**	**Least**
0-15	DM1,DH1,DM3,DH5,DM5,DH5	DH3
16-26	DM1,DH1,DM3,DH3	DH3
27-46	DH1,DM3,DH3	DH3
47-57	DM3,DH3	DH3
58-113	DM3,DH3,DH5	DH3
114-192	DH3,DH5	DH3
193-331	DH5	DH5
332-350	//	auto

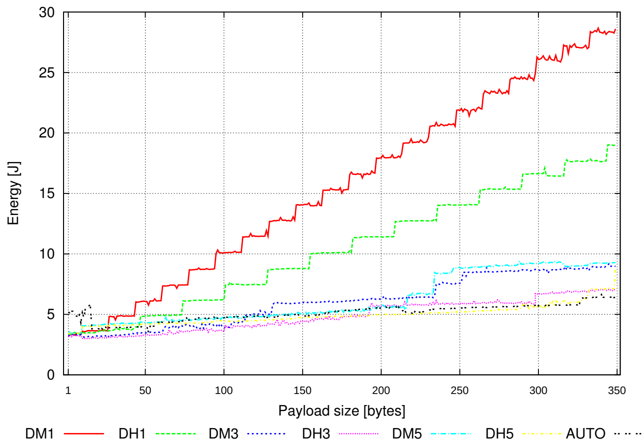

Figure 10: Energy consumption for 3000 transmissions using different packet types.

using DH3 and DM3 packets. Figure 11 shows that when increasing the distance between the phones, the time needed for transmission increases as well due to retransmissions, but DH3 packets still perform better than DM3 ones. This means that FEC is not giving any benefit to DM packets even when the distance between the phones reaches the edge of the Bluetooth's range.

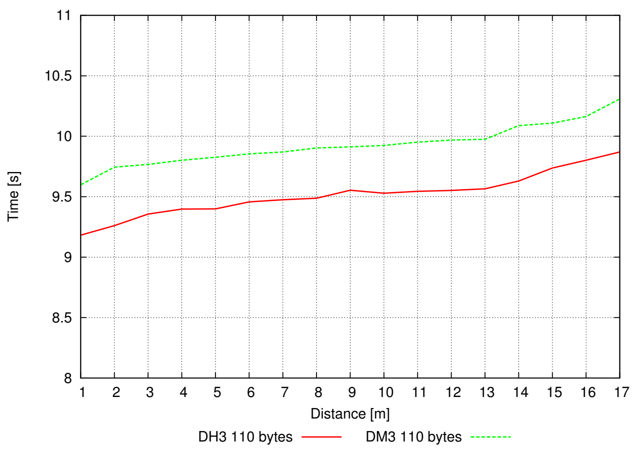

Figure 11: Time needed to transmit 3000 times a packet with payload of 110 bytes for different distances between the two phones. The two traces refer to DH3 and DM3 packet type.

Another possible cause of corruption of bytes can be the noise on the chipset as well. In the early days of Bluetooth this was an important issue, but in the last years the evolution of Bluetooth chipsets have increased the tolerance to noise interference. As a consequence, Enhanced Data Rate (EDR) implementation does not use FEC at all, as well as Ultra Low Power Bluetooth. The discussion with a leading Bluetooth chip manufacture concluded that *chips have become better . . . with receiver sensitivities of -90 dBm while in the early days they were in the 70's. Also, because of EDR, most architectures have go to an IQ based receiver that is more sensitive.*
In the actual implementation, packet types are selected according to the channel condition, but results have shown that energy savings can be achieved if an energy aware selection is made instead. Therefore, in order to save energy, one could think to select the packet type according to the payload to be sent and choosing the one that is more energy efficient. As shown in Figure 12, this as a positive impact on the performance in terms of throughput as well.

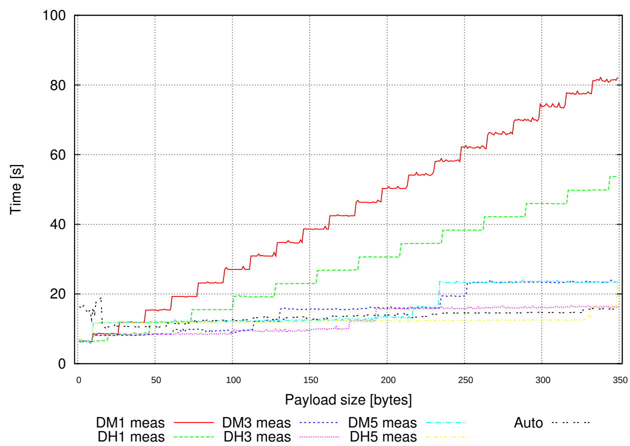

Figure 12: Time needed for 3000 transmissions using different packet types.

5 Conclusions

This paper investigates potentials of energy saving for Bluetooth technology when using asynchronous connectionless link (ACL) for data transmission. In fact Bluetooth provides different packet types, namely DM and DH packets. There are 6 different packet type in total and each of them has a different payload size. We have conducted an energy measurements campaign on commercial

mobile phones, namely Nokia N95 and Nokia N71 aimed to evaluate the performance of the different packet type usage. We have measured time, power and therefore energy consumption when sending data forcing the phone to use a specified packet type. We repeated the measurements for each packet type for a payload size varying from 1 to 350 bytes. Moreover we measured the performance when the phone selects the packet type automatically.
Results show that the packet type selection can influence the time and energy consumption. In fact using DH packets instead of DM ones is preferable in terms of energy and throughput. Moreover, letting the phone selecting the packet type is more energy unfriendly for most of the payload sizes. This is due to the fact that in the actual implementation of Bluetooth the packet type selection is based on the channel conditions and therefore a continuous adaptation can introduce some delays in the transmission. We have shown that energy savings are possible if packet types are selected in an energy aware fashion.

6 Acknowledgments

Authors would like to thank Nokia for providing technical support as well as mobile phones to carry out the measurement campaign. Special thanks to Mika Kuulusa, Gerard Bosch, Harri Pennanen, Nina Tammelin, and Per Moeller from Nokia. This work was partially financed by the X3MP project granted by Danish Ministry of Science, Technology and Innovation.

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Paper B

On the Impact of 2G and 3G Network Usage for Mobile Phones' Battery Consumption

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Abstract

Over the last years mobile phones had a remarkable evolution. From a simple device for voice communication, it became a full blown multimedia device with multiple features and appealing services. In parallel with the introduction of novel services, mobile devices became more and more energy-hungry reducing the operational time for the user. To extend the battery life of mobile phones is one of the top priorities for mobile phones' manufacturers. This paper presents results of power and energy consumption measurements conducted on mobile phones for 2G and 3G networks. The services under investigation were text messaging, voice and data. The paper reports larger energy consumption in 3G networks for text messaging and voice services than energy consumption in 2G networks. On the other side the 3G networks become more energy friendly when large volumes of data have to be sent. The results imply that mobile phones should switch the network in dependency of the service used to save the maximum amount of energy. As this handover consumes energy, we include its analysis in our measurements.

1 Introduction

The evolution of mobile phones in the last decade has been remarkable. In less than ten years the mobile phones, starting with voice services and text messaging, became real multimedia devices. This evolution is based on Moore's Law. According to Moore's Law, the number of transistors that can be inexpensively placed on an integrated circuit is doubling every 18 months. Over the last years mobile phones have been provided with better hardware and are becoming more powerful day by day. Music and video players, in-built GPS receivers, high data rate for Internet connection, short range communication technology (WLAN, Bluetooth, Near Field Communication), high resolution cameras are just a few examples of what smart-phones can offer. Many services have been created using these technologies, for example multi player games, location based services (LBS), mobile social networks, mobile banking, mobile web browsing, mobile VoIP. Moreover several applications have been developed to access these services such as *Fring* (a mobile client for VoIP), *ebuddy* (a mobile web messenger to interact with MSN, Yahoo, Google Talk, MySpace and AIM communities), *aka-aki* (a social network application), *The journey* (a mobile location based game) and so on. All these applications and services are using the wireless air interfaces of the phone for communicating. In Figure 1 power consumption for different mobile services is shown. It is clear from the plot that all the capabilities that imply the use of a wireless air interfaces are power-hungry, thus significantly reducing the battery life of the phone.

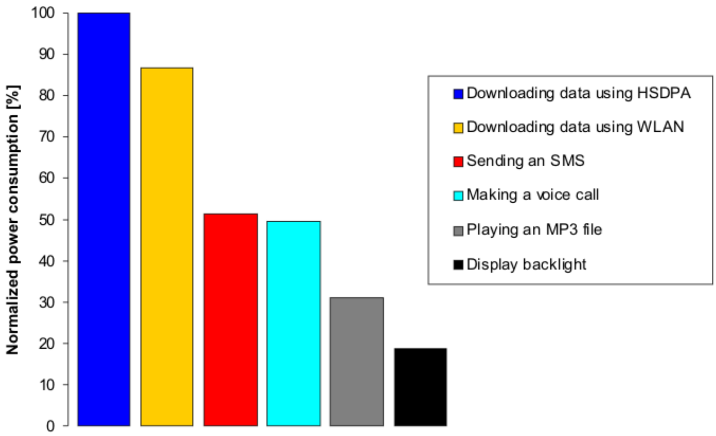

Figure 1: Power consumption for different phone's services normalized to the power consumption needed for downloading data using HSDPA.

This is a problem that mobile phones' manufacturers have to face because unfortunately not all aspects of computing technology develop according to Moore's law, and one of these is the battery. Most mobile phones are powered by lithium-ion batteries. These batteries are popular because they can offer many times the energy of other types of batteries in a fraction of the space. In the current state of the art, chemists cannot sufficiently increase the amount of energy created by the chemical reactions. At the moment the only way to create more powerful batteries is to make them larger. However this does not well match with the evolution of the mobile terminals which tend to have less room available for the battery in order to accommodate additional components and technologies.

Many attempts have been made to extend the battery life without renouncing to use the services that 3G phones offer. For example authors in [5] show the benefit of cooperation among mobile devices willing to share their wireless resources. Cooperation allows to reduce the energy consumption of mobile devices and at the same time to increase the quality of some services, such as file streaming or file downloading, as well as web browsing. Moreover authors in [8] describe another efficient way of saving energy in mobile VoIP. Instead of having a data connection open with WLAN when waiting for an incoming VoIP call, they suggest to use the GSM network as a wake-up signalling channel when the connection to the SIP server is needed.

To find the right strategy to save energy, knowledge of the amount of energy spent in every single action performed by the mobile phone is needed. We have made an extensive energy measurement campaign on a commercial mobile phone, the Nokia N95. In this paper we present several results to show the impact of 2G and 3G networks on the energy consumption of the mobile device focusing on voice services, Short Message Service (SMS) and data connection. In Section 2 a motivation for this work is given. In Section 3 the testbed used for the measurements is described and the results of measurements for voice, SMS and data connection are presented and discussed in Section 4.

2 Motivation

3G phones offer better services compared to 2G phones, especially regarding bit rate when downloading or uploading data. Moreover they can support data and voice traffic at the same time allowing video calls, for example. However, use of data services is only slowly becoming more widespread, and many costumers still use their phone mainly for voice and Short Message Service (SMS) and in a small portion for data services. Moreover, many areas still have limited 3G coverage and the phone continuously makes hand-offs from 2G to 3G network and viceversa as the mobile phones moves into and out of 3G coverage. Therefore being connected to a 3G network, especially when no data transmission is needed, has an high cost in terms of energy consumption. In this paper we present the results of the measurements made for the most widely used services, namely SMS, voice and data services.

SMS is one of the most remarkable success stories in the world of data communication. Already in January 2007 the number of active users of SMS text messaging exceeded two billion. The first SMS typed on a GSM phone was sent in late 1993. The initial growth was slow, but it had an incredible boost over the years. GSM Association reported that in the first three months 2001 more than 50 billion SMS were sent over the world's GSM networks. In November 2007 Gartner [7] forecasted 2.3 trillion messages will be sent across major markets worldwide in 2008, a 19.6% increase from 2007. The SMS technology has facilitated the development of text messaging. The connection between the text messaging and the SMS technology is so strong that for many users SMS is used as a synonym for a text message. Given this huge number of text messages exchanged in the world, it is important to know the amount of energy spent to send them. In Section 4.1 the results of the measurements for sending SMS of different size, and different received signal strength are presented.

The other very common service for mobile users is voice and one of the information that phone manufactures give in the specification of the device is the duration of the battery in standby and talking time. Actually this is one of the most important factors for people to choose a new phone.

As an example we cite the iPhone 3G. The battery life in talking time is shorter if the iPhone is connected to 3G networks (5 hours on 3G and 10 hours on 2G) as reported in the official website. Moreover, Apple suggests to its costumers some tips to save energy and make the battery last longer [1]. As shown in Figure 2, the first tip in the list reads: *"Using 3G cellular networks loads data faster, but may also decrease battery life, especially in areas with limited 3G coverage"*. In section 4.2 we will show the results of the measurements done for the

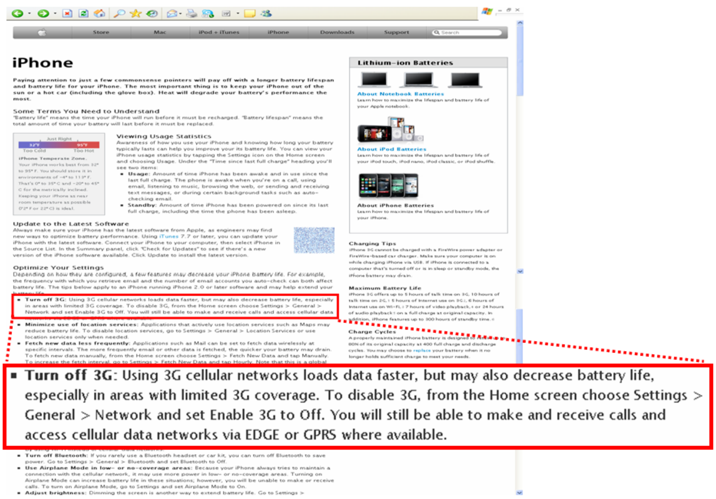

Figure 2: Web page of the Apple iPhone 3G.

voice service over both GSM and UMTS networks with the testbed described in Section 3.

3 Measurements testbed

The smartphone used for the measurements is a Nokia N95 [2] which is running Symbian OS as operating system. When making the measurements, we used scripts to control the phone. This allowed us to measure the consumption without interacting directly with the phone, avoiding to press keys and to have the backlight of the display turned on, which could lead to unprecise results. We used Python for S60 [10], [9] as programming language to develop the scripts for testing. We observe that there is no significant penalty in terms of energy and performance by using the Python environment compared to standard Symbian/C++ for the energy levels we deal with throughout this paper. The choice of the mentioned commercial device is due to several reasons. First of all it is a 3G phone and secondly it is able to run the in-built energy profiler [4] developed by Nokia. The Nokia Energy Profiler is an application running on the mobile device that allows to make measurements without any additional hardware. It provides the values for power, current, temperature, signal strength and CPU usage. To further check the correctness of the data measured by the energy profiler on the phone, the complete setup includes the AGILENT 66319D used as multimeter as shown in Figure 3. It is connected to a PC which is running the Agilent 14565B device characterization software, a tool designed for evaluation of portable battery powered device current profiles.

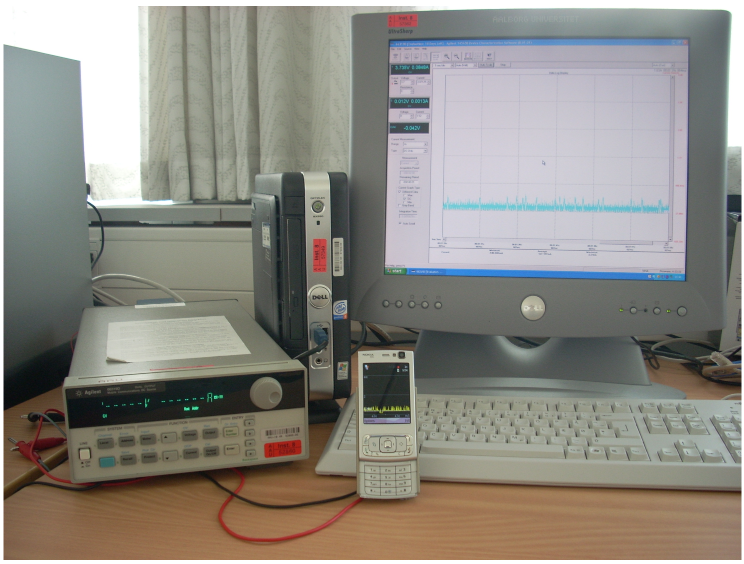

Figure 3: Setup for the measurements. The Nokia N95 connected to the AGILENT 66319D equipment.

We have compared results obtained with the energy profiler with the ones obtained with the Agilent 66319D. Figure 4 shows that the two plots match almost perfectly with each other proving that data given by the Nokia Energy Profiler reliable.

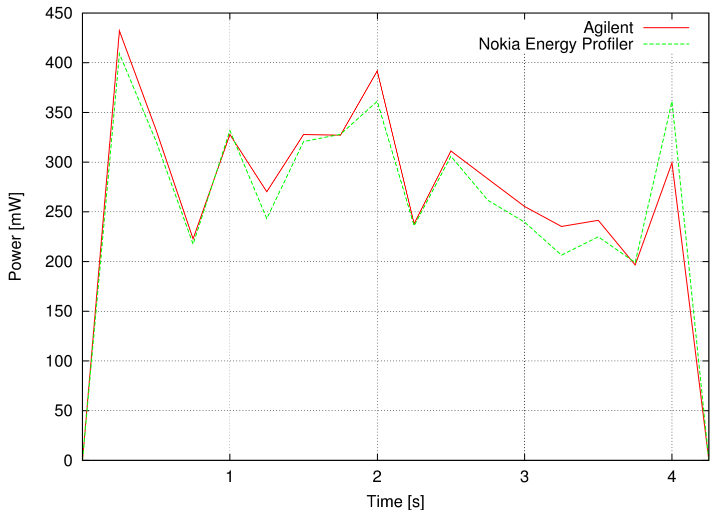

Figure 4: Comparison of data obtained with the Nokia Energy Profiler and the Agilent 66319D while sending an SMS.

4 Results and discussion

We now present the results of measurements for energy consumption made for SMS, voice and data services.

4.1 SMS

Text messages sent by using SMS can be encoded in different ways: the default GSM 7-bit alphabet, the 8-bit data alphabet, and the 16-bit UTF-16/UCS-2 alphabet. Depending on which alphabet the text is coded with, the maximum size per SMS is 160 7-bit characters, 140 8-bit characters, or 70 16-bit characters. It is possible to send longer texts by concatenating more messages with each other. Figure 5 shows the results of measurements done by sending messages of different sizes to evaluate how energy consumption is related to the length of the text. The messages were sent using both GSM and UMTS with a SIM card from TeliaSonera in Oulu, Finland.

We have sent 50 messages for each size and then plotted the average value of the energy spent. The phone was in the same position for all the measurements to have the smallest variation possible in the received signal strength. The plot clearly shows that the energy consumption increases linearly with the length of the message. The messages sent were 8-bit encoded, therefore it is possible to see

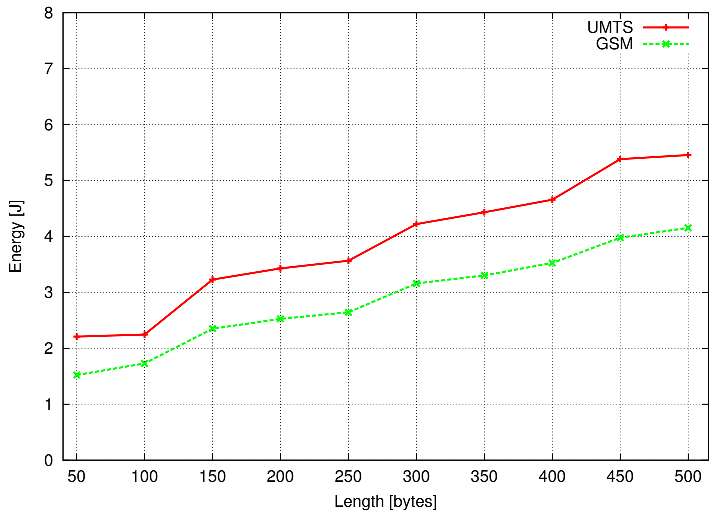

Figure 5: Energy spent for sending text messages with different length.

some jumps up in the energy consumption when two messages are concatenated, such as between 100-150, 250-300, and 400-450. It is interesting to notice that given a fixed length, sending an SMS using 3G is always more energy consuming than using GSM. The gap varies from 0.6 to 1.4 Joule. Another interesting relation exists between length of the messages and time needed for sending them. Figure 6 shows that the time increases with the growth of the size of the message and that the overall time needed is greater with GSM than with 3G. Moreover the gap between the two technologies increases linearly with the length of the text.

Authors in [6] have shown the benefit of using compression to save energy when sending short messages on mobile phones using SMS. The energy spent for compressing and decompressing messages is much less than the gain obtained by sending less data. Some software [3] is already available for downloading which is able to compress and decompress text messages. By using such a software, the energy for sending text messages can be reduced by up to 40%, depending on the compression level.

The plot in Figure 7 shows that the power level for GSM does not vary too much when the size of the text increases, whereas in the 3G case, it grows linearly with the length of the SMS.

Another factor which influences the power, the time, and therefore the energy, is the received signal strength. As shown in Figure 8 for both GSM and 3G,

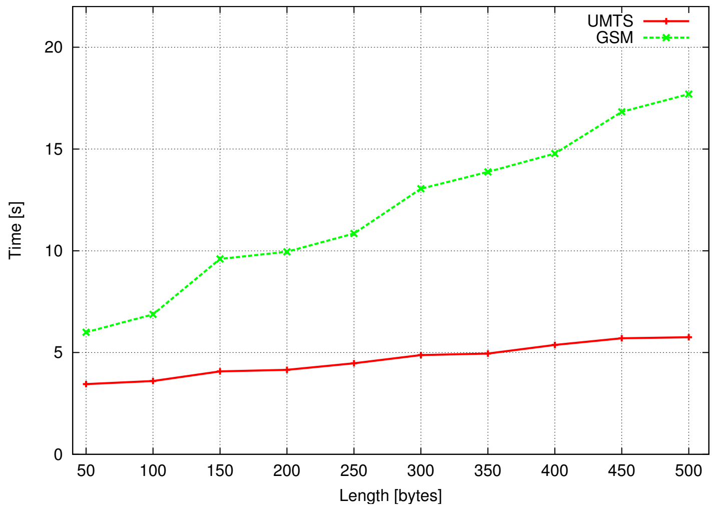

Figure 6: Time spent for sending text messages with different length using both GSM and UMTS.

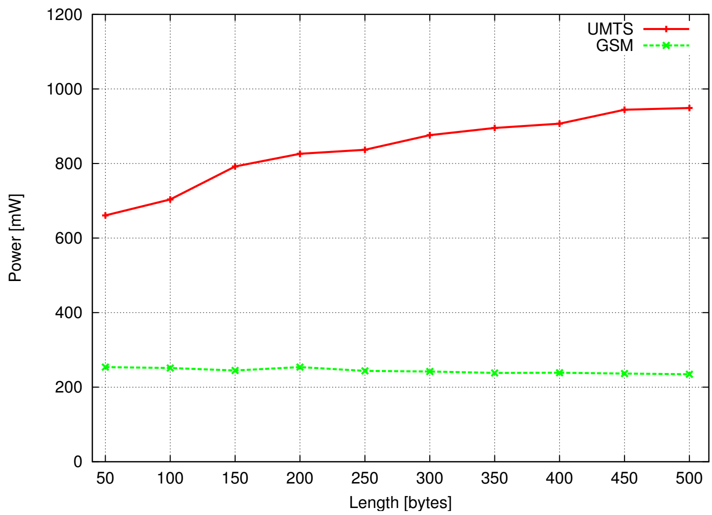

Figure 7: Power values for sending SMS of different size using both GSM and UMTS.

when the power of the received signal decreases, the time needed for sending the

SMS increases.

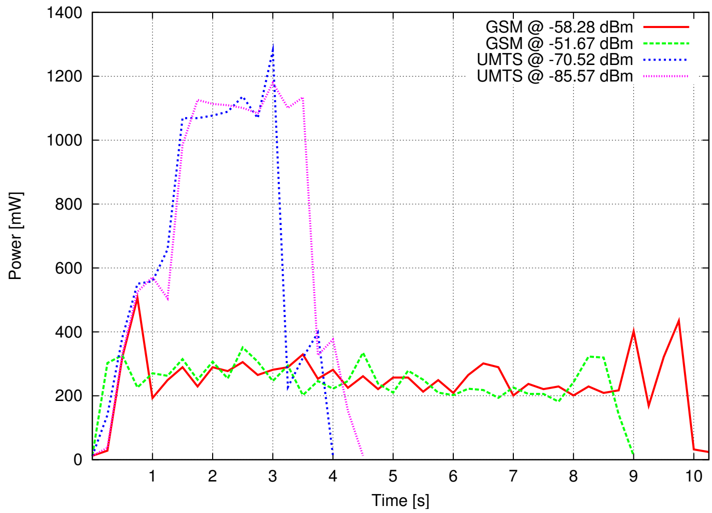

Figure 8: Power traces for sending 200 bytes using UMTS and GSM networks. The plot shows two traces for each network with different received signal strength.

As shown in Figure 9 the power levels increase as well when the received signal strength decreases and therefore, more energy is needed when the signal is weaker.

4.2 Voice

As mentioned in Section 2 the battery duration of mobile phones highly depends whether they are connected to GSM or 3G networks. In Table 1 are shown the values for power consumption on a Nokia N95 for both GSM and UMTS using the voice service, carried out with the testbed described in Section 3. The power values for the calls have been obtained by making and receiving a phone call of five minutes duration and calculating the average of the power levels. The power consumption during the idle time has been calculating averaging the power levels over eight hours of idle mode. All these tests have been performed using a SIM card from Sonofon in Aalborg, Denmark. The results show that making a call using GSM costs 46% less energy and receiving a call costs 50% less energy than using UMTS. Being idle while connected to a GSM network costs 41% less than UMTS. To give an idea of the amount of energy that can be saved by using GSM instead of UMTS for voice services, in Table 2 some examples are given. They show the substantial amount of energy that could be saved and used for other

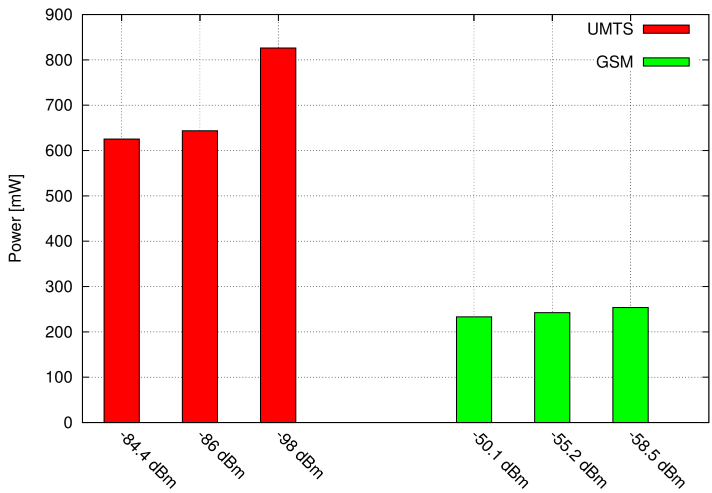

Figure 9: Mean power level for sending 200 bytes using UMTS and GSM. The plot shows histograms for different values of received signal strength.

Table 1: Power consumption for a Nokia N95 in different scenarios of voice service.

Scenario	**GSM**	**UMTS**
Receiving a voice call	612.7 mW	1224.3 mW
Making a voice call	683.6 mW	1265.7 mW
Idle mode	15.1 mW	25.3 mW

tasks. For example making a one hour voice call with GSM instead of UMTS, would allow to send more than 1000 text messages of 100 bytes.

4.3 Data connection

From a user perspective, it makes more sense to be all the time connected to the GSM network and switch to 3G only if data connection is needed. In fact the energy saved while using SMS or voice services can be used for other services offered by the 3G phones, such as Internet connection, VoIP, media and entertainment. On-demand use of 2G and 3G networks depending on the requested service, requires including this cost in the energy analysis. The results are shown in Table 3 and are obtained by averaging the values of 10 handoffs.

Figure 10 shows the plot of the mean values of energy per bit spent for down-

Table 2: Examples of energy savings by using GSM instead of UMTS for different scenarios.

Scenario	Time [hour]	Energy saved [J]
Idle mode	8	220
Making voice calls	1	2095

Table 3: Duration, power and energy consumption for making handoffs from GSM to UMTS and viceversa using a Nokia N95.

Handoff	Power [mW]	Time [s]	Energy [J]
GSM − > UMTS	1389.5	1,7	2,4
UMTS − > GSM	591.9	4,2	2,5

loading 500 KB of data for different data rates. When the phone is connected to the GSM network, the technology used for downloading is GPRS. In contrast, when connected to the UMTS network, HSDPA was used for downloading data. The plot shows clearly that the energy per bit decreases with the increase of the

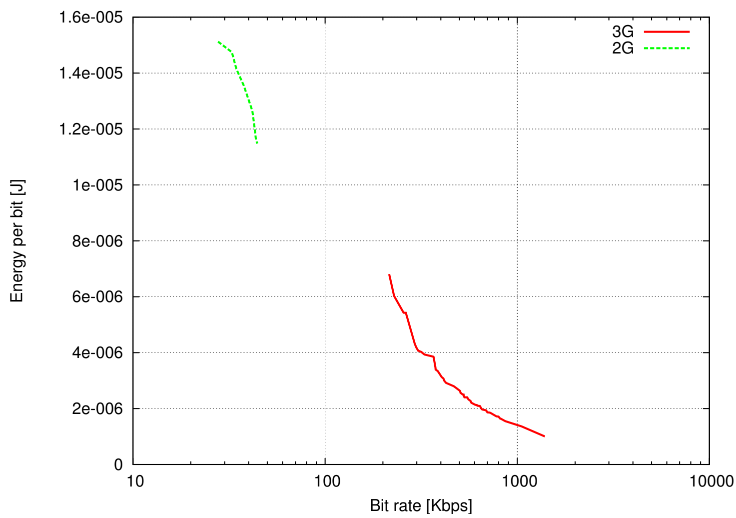

Figure 10: Energy per bit spent for different data rates when downloading a file of 500 KB on both GSM (GPRS) and UMTS (HSDPA) networks.

datarate for both data connections. Furthermore, the amount of energy per bit

Table 4: Energy comparison using 2G alone, 3G alone and the intelligent switching between the networks.

Service	**2G**	**3G**	**Switching**
50 SMS of 100 bytes	90 J	110 J	90 J
100 Mbytes downloading	10006.2 J	3512.1 J	3512.1 J
5 hours of voice calls	12304.8 J	22782.6 J	12304.8 J
50 handoffs			245 J
TOTAL	**22401.0 J**	**26404.7 J**	**16151.9 J**

spent for data download when connected to the UMTS network is significantly smaller than the one needed if using GPRS.
To give a better overview of the results presented, we give now an example of energy consumption for a monthly usage of mobile services. Let us consider a scenario where a user sends 50 SMS of 100 bytes, downloads 100 Mbytes of data, makes five hours of voice calls and 50 handoffs (only in case of the intelligent switching) per month. In Table 4 we show the values for the energy consumed in that specific scenario by using 2G alone, 3G alone and the intelligent switching between the networks. The table provides a clear overview of the impact that different services have on the energy consumption. Furthermore it shows the significant reduction in terms of energy when using the intelligent switching.

5 Conclusions

Mobile phones have appealing services and features which unfortunately drain a lot of the energy stored in a capacity limited battery. It is a common problem among phones manufacturers to find a way to extend battery life of their devices and allow users to use mobile services for a longer time. Furthermore network operators are interested in longer stand by times for the users as that may lead to higher use of their services. In this paper we presented the results of measurements conducted on a Nokia N95 to show the energy consumption for the most widely used services, namely SMS, voice and data using both GSM and UMTS.
For SMS, the results show that sending text messages using 3G is more energy consuming than using GSM. Moreover, we showed that the received signal strength has a high influence on the time needed for sending the message and therefore the energy.
Regarding voice services, we showed that being connected to the 3G network causes the phone to consume around 50% more energy. In fact, making a one hour call with GSM instead of UMTS, allows the phone save the amount of

energy needed to send more than 1000 SMS of 100 bytes.
On the other hand, when a data connection is needed, 3G networks offer higher data rates with lower consumption in terms of energy per bit. Most users have the possibility to set the network they would like to use, which gives them the possibility to switch between networks depending on the actual used service. To simplify this method for energy conservation, it is possible to develop a middleware solution that handles the switching depending on the used applications in a automated fashion. From a network operator point of view the question whether to use 2G and 3G is not based on the energy consumption but on the capacity of the available networks. Nevertheless as pointed out before also network operators have an interest to increase the battery life of the users' phones.

6 Acknowledgments

Authors would like to thank *DOCOMO Communications Laboratories Europe* for providing their support. This work was partially financed by the X3MP project granted by Danish Ministry of Science, Technology and Innovation.

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Paper C

Using Wake-up Signals for Energy Savings in Mobile Devices

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Abstract

Voice-over-IP (VoIP) has rapidly gained popularity in the last years, especially on smartphones platforms. In fact, WLAN chip-sets are becoming an essential part of smartphones, allowing users to access VoIP services from their mobile devices free of charge. On the other hand, the excessive energy consumption of the WLAN chip-set, limits the widespread use of VoIP on mobile phones. As most of the energy is spent when the WLAN is in idle mode waiting for an incoming call, a possible solution is to turn it off while a secondary air interface, with lower energy consumption, is used for monitoring calls. The WLAN card is turned on only upon the occurrence of an incoming call. In this article we describe two approaches to address this problem, namely the overlay and cooperative approaches. We present measurements of energy consumption carried out on a commercial device to show that the proposed solutions reduce the energy consumption for VoIP calls on smartphones over WLAN.

1 Introduction

People's habits have changed dramatically in the last years due to globalization. Nowadays it is very common to travel around the world and to be regularly in contact with people from other countries or even from other continents for both personal or business reasons. In general, people prefer to use voice services to communicate with each other. At the moment there are several voice services available for users to choose, namely *conventional wired-line*, *wireless circuit switches* and *wireless VoIP* (Voice over Internet Protocol) services.
However, due to these changes in the society, users demand a higher degree of mobility, allowing them to make and receive calls on the go. Moreover, users expect low costs for calls, especially for international ones. *Conventional voice services* are no longer meeting the demand of users for mobility, but on the other hand they offer fares reasonably low for voice calls. *Wireless circuit switches (cellular voice) services* offer high mobility, but unfortunately costs are much higher if compared to the conventional services, particularly if international roaming is involved. For all these reasons, *wireless VoIP services* have become very popular in recent years and seem to be very appealing if compared to conventional and cellular voice services.
One of the key factors for VoIP success is the significant cost reduction for voice communication. In fact, some applications for PC, such as Skype, Google Talk, MNS Messenger allow users to make VoIP calls within the same community free of charge. Moreover VoIP allows users to call landline and mobile numbers with unexpensive rates or, in some cases even for free (for example using software like VoipStunt and FreeCalls). Therefore costs for voice communication can be

dramatically reduced for companies and people making extensively international calls.
Another very important feature that VoIP provides, especially to people who travel extensively, is mobility. In fact, one can make or receive VoIP calls regardless of the location, as long as an Internet connection is available. This is no longer a problem as the number of Wi-Fi hotspots increases all the time. Along with the wide use of notebooks with Wi-Fi cards, the Internet access is much easier for users on the move. Moreover, in the last years, we have witnessed a rapid evolution of smartphones, which have become very powerful devices. As a consequence, it has been possible to port some software solutions for VoIP to the smartphone platforms, giving the users even more alternatives for being connected to the Internet. In fact smartphones are equipped with several air interfaces that can be used for network connectivity, such as Bluetooth, cellular and WLAN.
Now the question is which one of these available air interfaces users should use. There are three main factors to take into consideration for the choice, namely *connection fees*, *mobility* and *battery life of devices*.
Regarding connection fees, both Bluetooth and WLAN are free of charge in case of connections to an open network, whereas for cellular connection fees are applicable according to the amount of data exchanged. Even though lately, network operators are offering flat rate packages for data connection, prices are still prohibitive for users, especially when not connected to the home network.
Using cellular networks becomes more user friendly when we consider mobility, because the network coverage is larger than that of WLAN and even more of Bluetooth. However to have a decent quality for the VoIP service, the phone needs to be connected to 3G or 3.5G networks and some areas do not have a full coverage yet.
The last, but certainly not the least important, factor is the battery life of devices. Mobile phones are battery driven and therefore they have very limited energy resources. This is not only a problem for users, but for mobile service providers as well. If the phone runs out of battery, users cannot access mobile services any longer, reducing the revenues of providers. Therefore mobile phone manufacturers are very keen in developing solutions to extend the battery life. Using batteries with more capacity could be a trivial solution, but unfortunately their technological evolution does not follow the needs created by Moore's law. While the computational complexity is doubled every two years according to Moore, the battery capacity is doubling only every decade.
Another solution would be to choose the air interface which is more energy efficient. It is known that cellular data connections (both 2G and 3.5G) consume more energy than Bluetooth and WLAN for downloading and uploading data [**?**]. Moreover, WLAN can download faster while spending a similar amount of energy as Bluetooth. WLAN has several advantages compared to Bluetooth.

Table 1: Comparison of wireless technology suitable for mobile VoIP services.

Technology	**Mobility**	**Cost**	**Energy** (call)	**consumption** (waiting)
Cellular (2G/3G)	++	- -	+	+
WLAN	+	++	+	- -
Bluetooth	-	++	+	o

++: Very good, +: Good, o: Fairly good, -:Bad, - -: Very bad.

First of all, WLAN has a larger range of communication (up to 100 meters, whereas Bluetooth Class 2 range is at the most some 15 meters). Secondly, the number of WLAN hotspots for Internet access available in the world is much larger than the one of Bluetooth.

If we consider the key advantages and disadvantages for each technology suitable for mobile VoIP services (see Table 1), we conclude that there is not an ideal technology. Because of that, combining different technologies and taking the best out of each one, appears promising. Following that idea, we observe that WLAN offers a good tradeoff for the widespread adoption of VoIP on smartphones especially when talking about costs for connection, mobility and energy consumption for data exchange. However, VoIP services require to be connected continuously to the network, otherwise it is not possible to detect incoming calls. This means that the air interface to choose has to be energy friendly not only for exchanging data, but when it is working in idle mode (waiting for incoming calls) as well. Unfortunately WLAN has an high energy consumption in idle mode, therefore a considerable amount of energy is spent, just waiting for an incoming call.

In this article we address the problem of excessive energy consumption in idle mode when using VoIP services over WLAN. We present a solution where the WLAN interface is turned off and another technology (more energy efficient, i.e., GSM or Bluetooth) is used for monitoring incoming calls. The WLAN card is turned on only upon incoming call events.

2 Scenario overview

VoIP services use SIP (Session Initiation Protocol)[?], which is a signaling protocol used to create, manage and close sessions in an IP based network, for example a two-way voice call.

In Figure 1 an overview of a VoIP activity is shown to understand the main potential of energy savings throughout this article. We can distinguish several periods having the same characteristics, namely *calling frames*. Within a *calling frame* there are two sessions:

Waiting session: typically there are long periods of inactivity where the phone is connected to the SIP server and waiting for a call.

Calling session: during this interval the user makes or receives VoIP calls. The duration of this interval highly depends on the user habits.

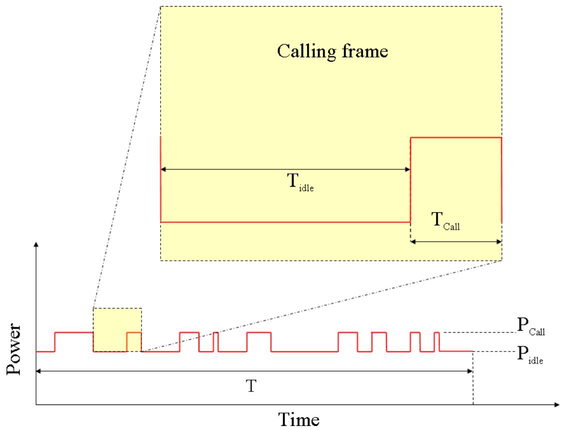


Figure 1: VoIP activity can be viewed as a collection of *calling frames*. Each of them is divided into *waiting session* and *calling session*.

Regardless of the duration of the two sessions, the phone uses more power during the *calling session*. However, the *waiting session* can last very long leading to a considerable amount of energy spent even though the power level is smaller.
Measurements done in [**?**] show that having a WLAN connection open causes an exhaustive consumption of energy, even when no data is transmitted. Switching off the IEEE802.11 card in this case will not be an option as incoming calls cannot be received. In [**?**] and [**?**], authors have shown the benefit in terms of energy saving of using a low power air interface to wake-up another one which has higher power consumption. This allows the high power air interface to be switched off for a longer period, and be woken up only when needed. In this article we introduce two strategies for saving energy using wake-up systems for VoIP applications over WLAN: *Overlay approach* (which is an extension of work done in [55]) and *Cooperative approach*. Both of them will be presented and discussed in detail in the next sections.

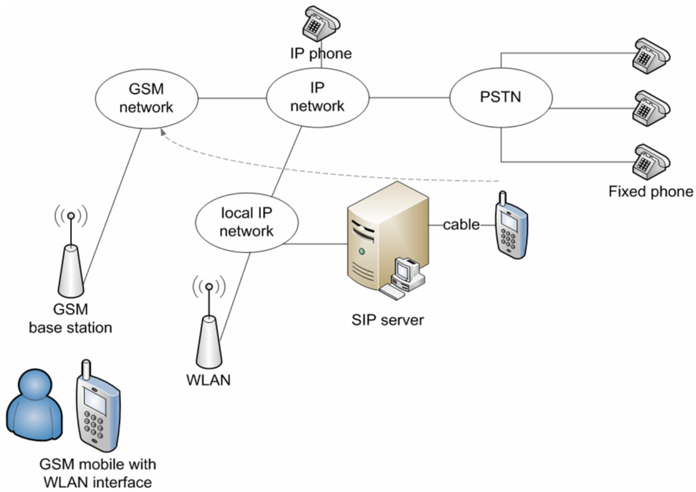


Figure 2: Overlay scenario overview: an IP phone tries to call a mobile phone using VoIP. The SIP server, before routing the call to the recipient mobile phone, will miss call to its GSM number over the cellular network to wake up the WLAN card. Once the phone is connected to the server, the call can be routed.

2.1 Overlay scenario

Figure 2 shows a possible implementation of a system based on the *Overlay approach*. Let us suppose to have a call from a VoIP client (sender) to a mobile phone (receiver) routed through a SIP server. Let us also suppose that the server has a mapping of the GSM number and VoIP ID of the recipient device. The SIP server, before routing the call to the recipient mobile phone, will call its GSM number over the cellular network. Upon receiving the call, the recipient mobile phone will identify the phone number of the server, understand that it is a wake-up call and suppress it.

From the mobile phone's perspective the incoming call by the server, identified by a certain number, is interpreted as a wake-up signal. It will now switch on the WLAN card, connect to the access point and wait for the incoming call. In case of high degree of mobility the wireless device could also ping the SIP server to make his new connection details available. As soon as the recipient devices has logged in, the server can route the call.

In this implementation, the *calling session* slightly differs from the traditional scenario where the recipient phone is continuously connected to the access point. As can be seen in Figure 3 the phone spends some extra energy every time it receives a call to set up the connection. The amount of energy spent during the

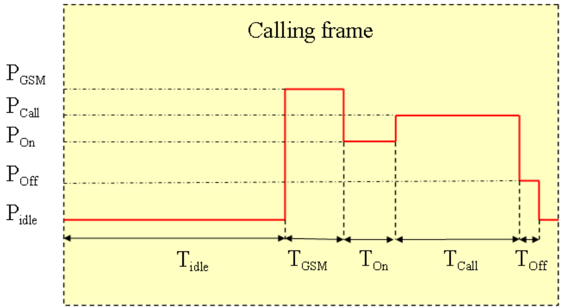


Figure 3: Calling frame for the *Overlay approach*. Some extra energy is needed to set up the connection compared to the calling frame of the traditional approach.

calling session can be calculated as:

$$E_{Tot} = P_{GSM} \cdot T_{GSM} + P_{On} \cdot T_{On} + P_{Call} \cdot T_{Call} + P_{Off} \cdot T_{Off}, \tag{1}$$

where P_{GSM}, T_{GSM}, P_{On}, T_{On}, P_{Call}, T_{Call}, P_{Off} and T_{Off} are respectively the power and the time spent for receiving and suppress the incoming GSM wake-up call, for switching on the WLAN card and connecting to the access point, for making the VoIP call for disconnecting from the access point and switching off the WLAN card.

As mentioned before, the duration and the energy spent for the VoIP call itself do not depend on the approach we use, therefore in order to compare the *Overlay approach* to the traditional one, we can take out the energy spent during the call from Equation 1. Equation 2 shows the formula for calculating the extra amount of energy spent per call with the *Overlay approach*.

$$E_{Setup} = P_{GSM} \cdot T_{GSM} + P_{On} \cdot T_{On} + P_{Off} \cdot T_{Off}. \tag{2}$$

2.2 Cooperative scenario

A second approach for energy saving by wake-up calls is inspired by cooperation. This approach is only accessible for users that are able to cooperate among each other. Due to the space limitations cooperative wireless networks will not be discussed in detail, but the interested reader is referred to [**?**] for an in-depth introduction.

For the ease of understanding, let us consider a group of users gathered in the

same place within short-range distance. Let us assume that all their phones are close to each other and that they are all waiting for an incoming VoIP call over WLAN. This could be for example a typical office scenario. To save energy some of the mobile phones in the group can switch off their WLAN, whereas one of them, referred as watchdog, can be connected to the access point. Whenever the access point has an incoming call for a device in the group, the watchdog will notify the recipient of the call to switch on the WLAN and to connect to the access point.
Figure 4 shows an example of notification system based on RFID (Radio Frequency IDentification) technology [?]. The system could be improved using coded messages to wake-up dedicated devices. The notification system can be

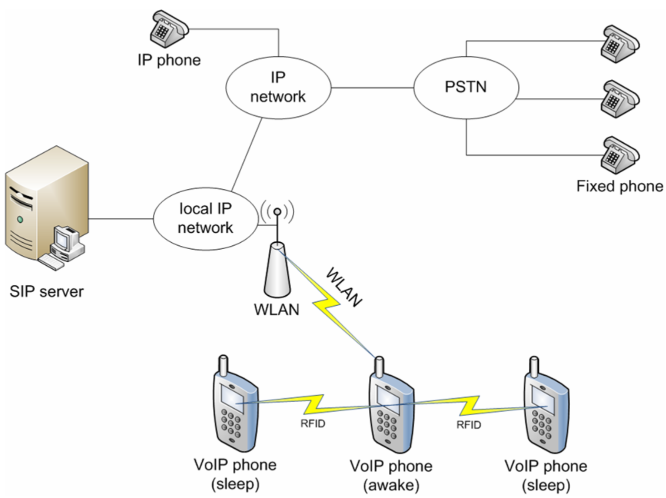


Figure 4: Notification system for a cooperative scenario. The watchdog upon receiving an incoming call for one of the mobile phones in the group, wakes them up using RFID or UHF technology. By using coded messages, only the interested phone will wake up.

done using different technologies as long as they are more energy efficient compared to WLAN. For example Bluetooth could be a choice for signalling as it consumes less power than WLAN [?]. More technologies to be used as wake-up systems are under investigation at the moment. Nevertheless, to give the reader a better insight, some examples are discussed in the sequel.
Many smartphones have a built-in accelerometer which could be used for wake-

up. If the group of phone is lying on the same surface, on a table for example, the watchdog could vibrate and the phones will detect the vibration with the accelerometer and wake up. Another concept is to use the light sensor embedded in some phones which can retrieve the light intensity to detect a particular light pattern. The watchdog creates visible light signals using the camera flash to wake the neighbors up. We have used some of these ideas for testing issues.

3 Measurements and results

In order to quantify the values of the single parameters in Equation 2, energy measurements have been carried out. In this section the measurements setup and the results are presented.
The smartphone used for the measurements is a Nokia N95 which is running Symbian OS as operating system. We used Python for S60 [**?**], [**?**] as programming language to develop scripts for testing. We claim here that there is no significant penalty in terms of energy and performance by using the Python environment compared to standard Symbian/C++ for the energy levels we deal with throughout this article.
The choice of the mentioned commercial device is due to several reasons. First of all it is equipped with a WLAN card. Secondly it is able to run the in-built energy profiler [**?**] developed by Nokia. The energy profiler is an application on the mobile device that allows to make measurements without any additional hardware. It logs the values for power with a sample rate of 250ms.
However, to check the correctness of the data given by the energy profiler on the phone, the complete setup includes the AGILENT 66319D used as multimeter as shown in Figure 3. It is connected to a PC which is running the Agilent 14565B device characterization software, a tool designed for evaluation of portable battery powered device current profiles.
We have compared results obtained with the energy profiler with the ones obtained with the Agilent 66319D. Figure 4 shows that the two traces match almost perfectly with each other proving that the data given by the energy profiler is accurate. Therefore we used the Nokia energy profiler to test every single action performed by the phone during the *calling session* of the *Overlay approach* separately.
Each test has been repeated several times and the calculations of the energy consumed have been done considering the mean values of power consumption and the time duration for each single action. For all the measurements the backlight of the display was off and in case of the incoming GSM call, the latter one is intercepted before the phone rings, avoiding any extra energy consumption. Moreover, during the measurements the phone was always connected to the GSM network to better emulate the real case scenario and other air interfaces such as

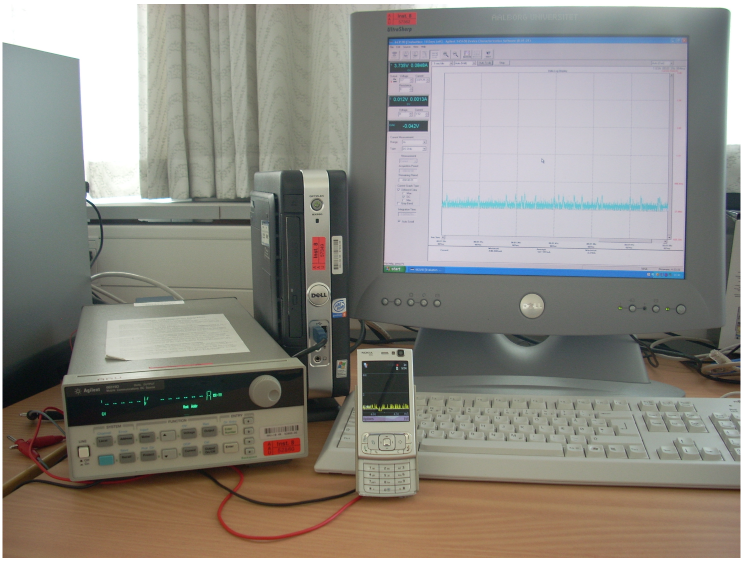


Figure 5: Setup for the measurements. The N95 connected to the AGILENT 66319D equipment and running the Nokia Energy Profiler.

Bluetooth, were switched off.
Figure 4 shows the plot of the power consumption over the time for connecting to the WLAN access point. The test consists of two steps: switching on the WLAN card and connecting to the access point. We have assumed that the phone connects to a predefined access point without searching for it. Figure **??** shows the plot of the power consumption over the time for receiving and suppressing an incoming GSM call. During this test the WLAN card was switched off. Figure **??** shows the plot of the power consumption over the time for disconnecting the phone from the access point and turn off the WLAN card. Figure **??** shows the plot of the power consumption over the time when the phone is connected to an access point but is not transmitting nor receiving data. This is the case of the *waiting session* with the traditional approach. Figure **??** shows the plot of the power consumption over the time when the phone is connected to the GSM network in idle mode. This is the case of the *waiting session* with the *Overlay approach*.
The two plots prove that GSM is more energy friendly in idle mode than WLAN.

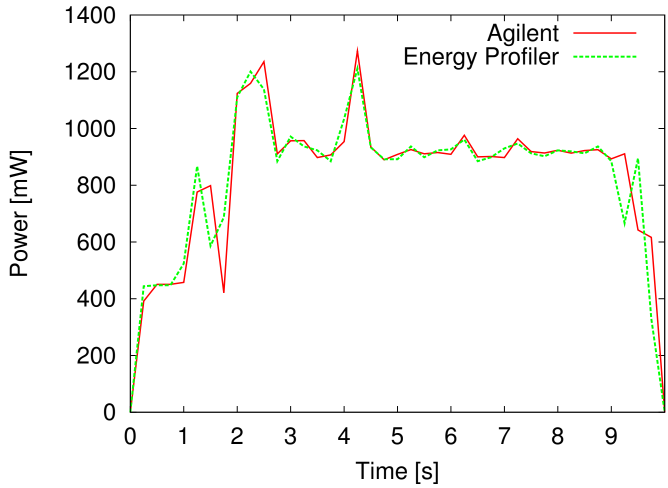


Figure 6: Comparison of data obtained with the energy profiler and the Agilent 66319D while measuring the connection of the phone to a WLAN access point.

4 Discussion

In order to compare the traditional approach with the overlay one, we need to calculate the energy spent by the two approaches.
The energy for the traditional approach E_{Trad} is given in **??**

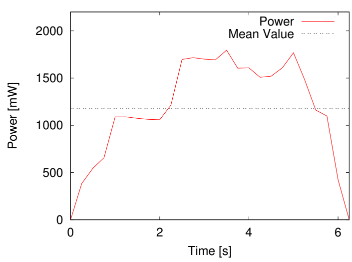
$$E_{Trad} = E_{WLAN,i} + N \cdot E_{Call}, \tag{3}$$

where $E_{WLAN,i}$ is the energy spent for being connected to a WLAN access point in idle mode, N is the number of calls during an interval of time T and E_{Call} is the energy spent during the VoIP call itself.
Equation **??** gives the calculation for the energy spent in the *Overlay approach*.

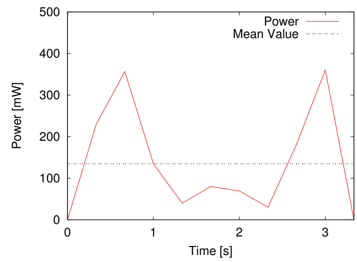
$$E_{Over} = E_{GSM,i} + N \cdot E_{Call} + N \cdot E_{Setup}, \tag{4}$$

where $E_{GSM,i}$ is the energy spent being connected to the GSM network and in idle mode and E_{Setup} is the energy in Equation 2. We can define an energy gain when using the *Overlay approach* as the difference of E_{Trad} minus E_{Over}, as shown in Equation **??**.

$$E_{Gain} = E_{WLAN,i} - E_{GSM,i} - N \cdot E_{Setup}, \tag{5}$$

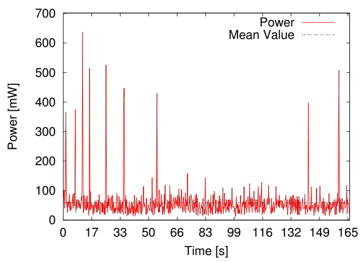


(a) Power consumption for receiving and suppressing an incoming GSM call from the SIP server.

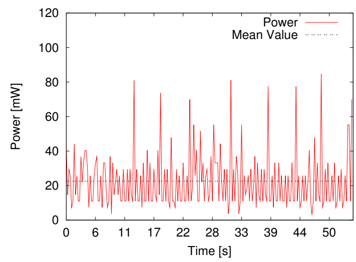


(b) Power consumption for disconnecting from the access point and switch the off the WLAN card.

Figure 7: Power consumptions traces for the different action needed to set up the connection in the overlay approach.



(a) Power consumption while connected to the WLAN and being in idle mode.



(b) Power consumption while being connected to the GSM network with no activity. A SIM card from the danish operator Sonofon has been used for measurements.

Figure 8: Power consumptions traces for being connected to WLAN and GSM networks.

Table 2: Power consumption, duration and energy of an Nokia N95 for different scenarios

Scenario	**Power**	**Time**	**Energy**
Incoming GSM call	1175.4 mW (P_{GSM})	6.5 s	7.64 J
Connecting to WLAN	868.5 mW (P_{On})	9.5 s	8.25 J
Disconnecting from WLAN	134.8 mW (P_{Off})	2.8 s	0.37 J
Connected to WLAN - idle	58.4 mW ($P_{WLAN,i}$)		
GSM - idle	20.2 mW ($P_{GSM,i}$)		

where

$$E_{WLAN,i} = (T - N \cdot T_{Call}) \cdot P_{WLAN,i} \tag{6}$$

and

$$E_{GSM,i} = (T - N \cdot T_{Call} - N \cdot T_{Setup}) \cdot P_{GSM,i}. \tag{7}$$

If we define a factor G as:

$$G = P_{WLAN,i} - P_{GSM,i} = 0.0382W, \tag{8}$$

by replacing the expressions of Equations **??** and **??** in Equation **??**, we obtain Equation **??**.

$$\begin{aligned} E_{Gain} &= T \cdot G - N \cdot T_{Call} \cdot G + N(T_{Setup} \cdot P_{GSM,i} - E_{Setup}) = \\ &= T \cdot G - N(T_{Call} \cdot G + E_{Setup} - T_{Setup} \cdot P_{GSM,i}). \end{aligned} \tag{9}$$

Using the values for T_{Setup}, $P_{GSM,i}$, E_{Setup} given in Table **??** for Equation **??** we obtain the cost function of the energy gain in Equation **??**:

$$E_{Gain} = T \cdot G - N(T_{Call} \cdot G + 15.88\ J), \tag{10}$$

where T is the duration of the all VoIP activities as in Figure 1, N is the number of calls received within the time T and T_{Call} is the mean value of the duration of the calls.
Plugging in Equation **??** the value of G given in Equation **??**, the gain E_{Gain} is greater then zero when:

$$N < \frac{T}{T_{Call} + 416\ s}. \tag{11}$$

Whether the proposed approach is beneficial for the user in terms of energy depends on some parameters related to the used technology (T_{Setup}, $P_{GSM,i}$, $P_{WLAN,i}$ and E_{Setup}) and some others related to the user habits (N, T and T_{Call}).

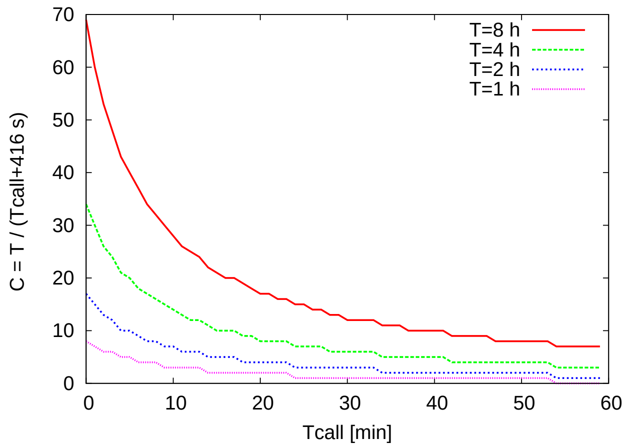


Figure 9: Cost factor C plotted for different values of T.

Table 3: Energy gain examples for different values of T, T_{Call} and N.

User	T_{Call}	T	N	E_{Gain}
User 1	15 min	8 h	20	92.5 J
User 2	10 min	8 h	10	711 J
User 3	7 min	8 h	5	940 J
User 4	20 min	8 h	25	-445.8 J

In Figure **??** the cost factor C=$\frac{T}{T_{Call}+416\ s}$ is plotted versus T_{Call} for different values of T. Given T and T_{Call}, if the cost factor C falls in the area below the curve, the energy gain using the overlay approach is positive. To help the reader to understand this issue better, we give some example in the following.
Let us assume to have four users using VoIP services on their mobile phones according to parameters T, T_{Call} and N shown in Table **??**.
The first three users have an energy gain which is still positive, even for User 1 which has a high mean duration of the calls, receiving 20 calls within 8 hours.

To evaluate the energy savings in case of the *cooperative approach*, let us assume K mobile phones forming a cooperative cluster. As described in Section 2.2 one out of K, referred as the watchdog, is connected continuously to the access point. Upon receiving a notification from the SIP server of an incoming call for any phone in the cluster, it will wake up the phone. We assume in the following that the wake-up notification system is spending a very little amount of energy (for example using RFID) and therefore we will ignore it in the calculations. The overall energy for the traditional approach for K terminals E_{Trad} is given in Equation **??**.

$$E_{Trad} = \sum_{k}^{K} (T_k - N_k \cdot T_{Call,k}) \cdot P_{WLAN,i} + N_k \cdot E_{Call,k} \tag{12}$$

The energy for the cooperative approach E_{Coop} for K-1 phones (E_k) and the watchdog (E_{WD}), is given in Equation **??**.

$$E_{Coop} = E_{WD} + \sum_{k}^{K-1} E_k, \tag{13}$$

where E_{WD} and E_k are given in Equations **??** and **??**.

$$E_{WD} = (T_{WD} - N_{WD} \cdot T_{Call,WD}) \cdot P_{WLAN,i} + N_{WD} \cdot E_{Call,WD} \tag{14}$$

$$E_k = N_k \cdot (E_{Call,k} + E_{Setup,Coop}), \tag{15}$$

where $E_{Setup,Coop}$ is the energy spent for connecting and disconnecting to the access point and this value is calculated in Equation **??** using the values of Table **??**.

$$E_{Setup,Coop} = T_{On} \cdot P_{On} + T_{Off} \cdot P_{Off} = 8.62\ J \tag{16}$$

The energy saved by using the cooperative approach can be finally written as:

$$\begin{aligned} E_{Gain,Coop} &= E_{Trad} - E_{Coop} = \qquad (17)\\ &= \sum_{k}^{K-1} (T_k - N_k \cdot T_{Call,k}) \cdot P_{WLAN,i} - N_k \cdot E_{Setup,Coop}. \end{aligned}$$

5 Conclusions

In this article we addressed the problem of excessive energy consumption in idle mode when using VoIP services over WLAN. We present a solution where the WLAN interface is turned off and another technology (more energy efficient, i.e., GSM, Bluetooth or RFID) is used for monitoring incoming calls. The WLAN card is turned on only upon incoming call events. Two different ways of implementing such a wake-up system have been presented, namely *overlay* (an extension of work done in [55]) and *cooperative* approach. Analytical results were presented and showed the benefit of the two approaches. This has been supported by measurements of energy consumption on an commercial device (Nokia N95). Finally four different user cases have been analyzed for the overlay approach showing that the wake-up system can reduce significantly the energy consumption of a mobile phone for VoIP services when compared to the conventional approach. It has been shown that the overall gain of the proposed approaches depends heavily on the users' call activity. Nevertheless, for a broad range of user call activities a clear gain by the different approaches has been demonstrated.

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Paper D

Energy Saving Aspects for Mobile Device Exploiting Heterogeneous Wireless Networks

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Original layout revisited

1 Introduction and Motivation

Mobile phones have been undergoing a breathtaking evolution over the last decade starting from simple mobile phones with only voice services towards the transition of smart phones offering Internet access, localization information and even more. It seems that there are simply no limitations for mobile devices getting smaller, offering higher data rates, brighter displays. Unfortunately this assumption is not correct. The limiting factor is known, namely the energy and power consumption of mobile devices being battery driven. As the complexity within the mobile device is increasing dramatically due to new services such as GPS modules, digital photo cameras, mp3 players and others, the improvement of battery capacity is quite moderate. The complexity increase of the mobile device is related to the fact that mobile handset vendors need new services to market their products and therefore exploit all the computational power of the given hardware, which is following Moore's law. Even the wireless air interfaces are getting more and more complex starting from simple TDMA systems towards the planned OFDMA/MIMO systems for the 4G wireless communication systems. The increased complexity has two key impacts. First, the enormous power consumption will lead to heating problems. Thus, the mobile device cannot cope with the heat using passive cooling anymore and active cooling would be necessary. To illustrate the problem of heating, Figure 1 and 2 show the temperature for a Nokia N95 in the offline mode and for WLAN IEEE802.11b/g downloading, respectively. The temperature difference is approximately 8 degrees Celsius. The situation could be even worse if the mobile device would be covered by holding it in the hand.

Figure 1: Thermal Plot For N95 Device Using WLAN In Offline Mode $(28,5C)$.

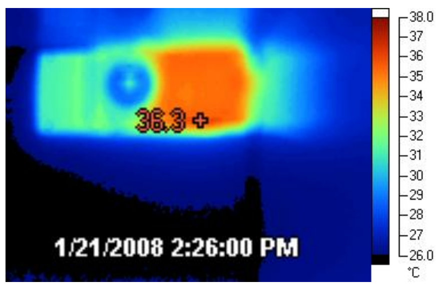

Figure 2: Thermal Plot For N95 Device Using WLAN IEEE 802.11b/g $(36,3C)$.

Secondly, the increased energy consumption would lead to lower stand-by times. Those stand-by times are limiting the time a customer can use its mobile device, which in turn makes the customer as well as the network operator unsatisfied. The customer cannot use any service and the network operator does not make any revenue. In other words, the degree on mobility for the customer depends on mobile device with low recharge cycles. That energy consumption is not only a problem of the future can be derived by Apples announcement that battery life was the main reason for the delay behind a faster 3G version of their iPhone. As given in [2], Steve Jobs said:

The 3G chipsets that are available to semiconductors work reasonably well except for power. They are real power hogs. So as you know, the handset battery life used to be 5-6 hours for GSM, but when we got to 3G they got cut in half. Most 3G phones have battery lives of 2-3 hours.

As 4G mobile phones will be even more complex than 3G phones, the question arises how the battery should cope with this new challenge. The increase in battery consumption by mobile phones is the reason that public battery chargers at airport and hotels are getting more diffuse. Those public chargers have several cable plugs for different mobile phones to charge the device, but the user needs to pay several dollars for the service — energy has a price!

Therefore the main focus in this chapter is the energy saving potential for mobile devices exploiting heterogeneous wireless network combinations. Besides the cellular air interfaces, mobile devices are equipped with several local area network technologies such as Bluetooth or WLAN 802.11. The different heterogeneous wireless technologies lead to energy savings if they are used properly. By the example of cooperative wireless networks, energy saving potentials are derived for different heterogeneous wireless technology combination.

In contrast to cellular systems, where the mobile devices are only connected to the base station (see Figure 3), in cooperative wireless networks, the mobile device, in addition to the cellular communication, will establish short range links to neighboring mobile devices within its proximity (see Figure 4). In prior work [3, 5] it has been shown that the newly formed cooperative cluster, also referred as wireless grid, can offer each participating mobile device a better performance in terms of data rate, delay, robustness, security, and energy consumption in contrast to any stand alone device. The improved data rate, delay, and robustness comes obviously by the accumulated cellular links with its inherent diversity. The decreased energy consumption is introduced in [4] for the first time and extended in this book chapter for multiple combinations of heterogeneous wireless networks. In a nutshell, as long as the energy per bit ratio is better in the short range connection than the cellular link, the cooperation will improve the energy consumption. This is the case for all available and future wireless technologies as the path loss is much smaller on the short range communication (around 10 m) than the cellular one (several 100 m).

In this chapter the energy consumption of all embedded wireless communication technologies that can be found on any commercially available smart phone is presented, namely cellular networks, IEEE802.11 and Bluetooth. Knowing

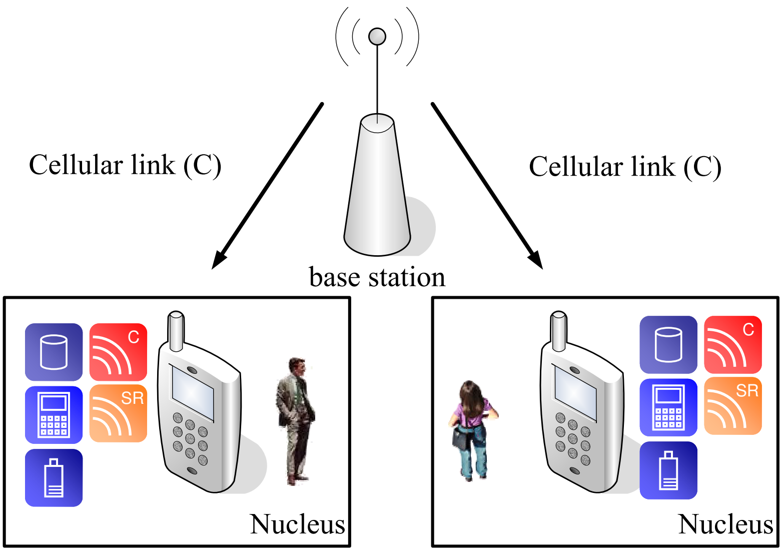

Figure 3: State of the Art Architecture.

about the energy consumption of the individual wireless technologies, adaptive schemes to switch among those technologies are presented using the example of cooperation among mobile devices.

2 General Notation and Assumption

Three different architectures using cooperation among the mobile devices are given in Figure 5. For all three architectures, it is assumed that the overall access point is *seeding* sub-streams into the mobile devices. Two different application scenarios are taking into consideration, namely *streaming* and *file download*. In case of streaming, the mobile devices of one given cooperation cluster listen on different multicast channels of the access point. A mobile device that is not cooperating with other mobile devices needs to receive all sub-streams by itself. Cooperating device will receive only a subset of those channels, in the extreme only one. An example of the streaming service could be a live stream of a sport event. In the case of file download, the access point is setting up several dedicated channels for each mobile device and therefore parallel download from the network is possible. The cooperating devices will receive the partial information over the cellular link and then combine those information over the short range link. An

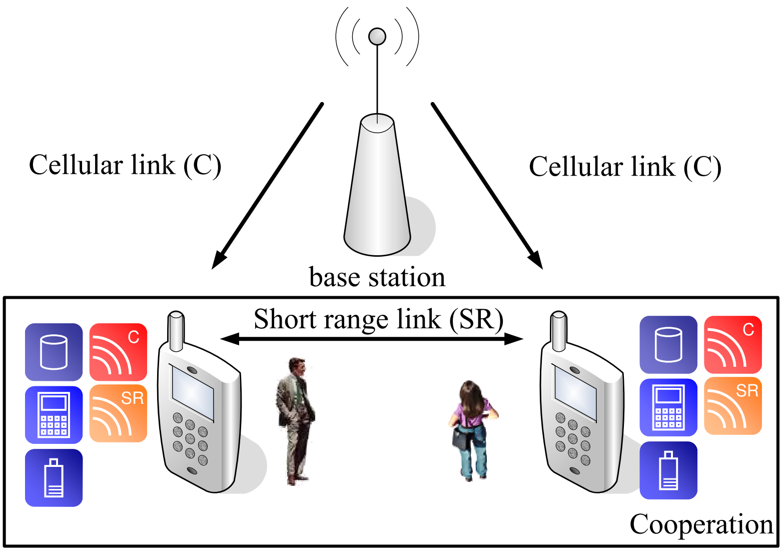

Figure 4: Cooperative Architecture.

example could be a download of gaming maps or file download a la BitTorrent. To build up the different architectures three different technology combinations are assumed:

- Cellular 3G and IEEE802.11 WLAN (3G/WLAN)
- Cellular 3G and Bluetoothv2.0 without Broadcast (3G/BTwoBr)
- Cellular 3G and Bluetoothv2.0 with Broadcast (3G/BTwBr)

It is out of the scope of this document to describe the single technologies in detail, but it is noted here that all mobile devices can communicate directly with each other using IEEE802.11. This is not the case for Bluetooth that has the concept of a master connected to a maximum number of seven active slaves. The slaves can only communicate via their master with each other and more data exchange is needed here. How much data is exchanged depends on the broadcast capability of the master. In case the master cannot broadcast packets to its slaves, obviously the number of transmission is larger than for the case the master is able to broadcast. Nevertheless, in both cases more packets are transmitted than in the 3G/WLAN case.

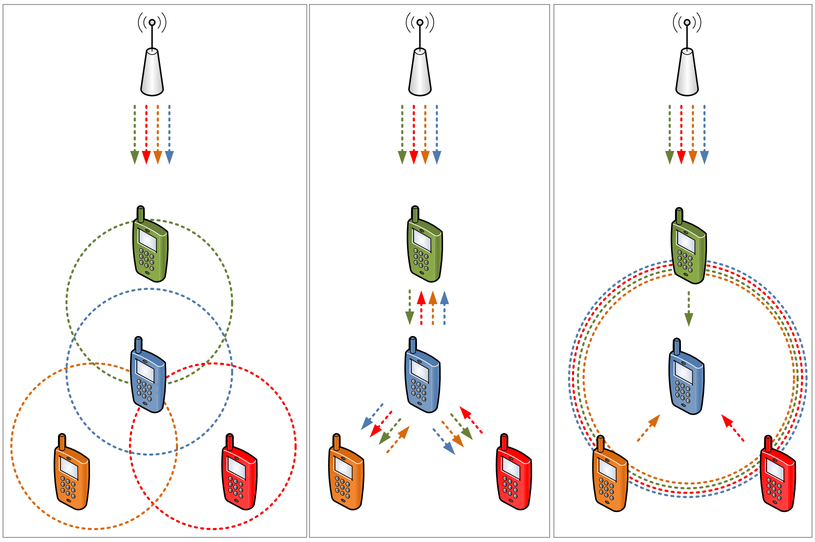

Figure 5: Three different architectures for cooperative wireless networking.

In Table 2 the notation for the following work is given. J is the number of mobile devices within a cooperative cluster served by one access point. As each mobile devices is using two wireless technologies for the cooperation, the overall energy consumption in this case, namely E_{Coop}, is composed out of $E_{overlay}$ and $E_{short\ range}$. To answer the question whether cooperation is beneficial in terms of energy consumption, E_{Coop} has to be compared with E_{noCoop}, which is the energy for a stand-alone mobile device with only one active wireless technology (only the cellular one and no short range). The energy saving S is given in Equation 2.

$$E_{Coop} = E_{overlay} + E_{short\ range} \tag{1}$$

$$S = 1 - \frac{E_{Coop}}{E_{noCoop}} \tag{2}$$

In Figure 6 the general notation for frames, slots, and mini-slots is given. A frame is the time period the centralized access point is conveying J slots. One slot out of J can be used to convey one of the multicast channels introduced beforehand. A frame has the nominal length of 1 and as a result of that, a slot has the length $1/J$. The transmission on the short range can be realized at a rate Z times larger than on the cellular link. If a mobile device is *forwarding*

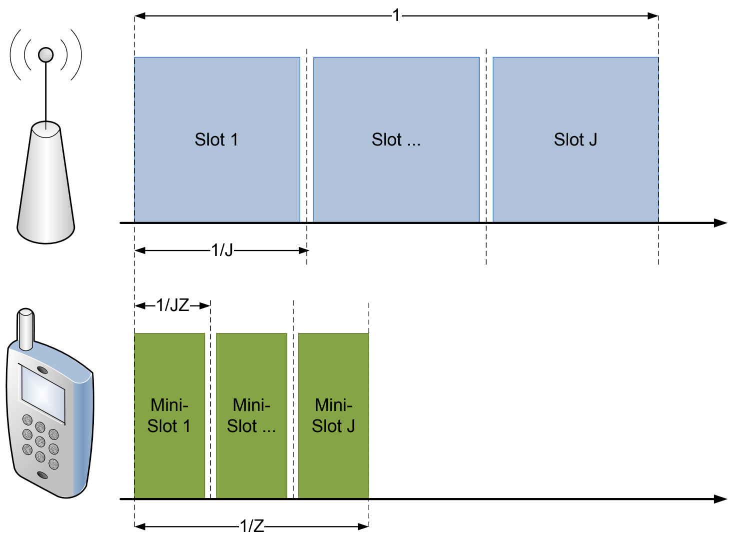

Figure 6: General notation for frames, slots, and mini-slots.

one slot, a time period of $1/JZ$ is needed on the short range link and referred to as mini-slot. Forwarding all mini slots will take $1/Z$.

As it can be seen by Figure 6, the energy consumption E_{Coop} is composed out of transmitting (tx), receiving (rx), and idle (i) phases.

$$E_{Coop} = \underbrace{E_{c,rx} + E_{c,i}}_{overlay\ contribution} + \underbrace{E_{sr,tx} + E_{sr,rx} + E_{sr,i}}_{short\ range\ contribution} \quad (3)$$

The individual energy values depend on the power level of that phase and the related time the mobile device is in that phase. The power values and the value Z is given by the technology used, while J depends on the scenario. The power levels can be measured and are presented in Section 3. The time values $t_{c,rx}$ and others are calculated in later sections.

$$E_{Coop} = \underbrace{t_{c,rx} \cdot P_{c,rx} + t_{c,i} \cdot P_{c,i}}_{cellular\ contribution} + \underbrace{t_{sr,tx} \cdot P_{sr,tx} + t_{sr,rx} \cdot P_{sr,rx} + t_{sr,i} \cdot P_{sr,i}}_{short\ range\ contribution} \quad (4)$$

Table 1: Notation

J	number of cooperative mobile devices
Z	ratio of short range data rate and cellular data rate
S	energy savings for cooperation compared with no cooperation
D	delay to provide a given service
α	auxiliary variable
$P_{c,rx}$	power level for receiving state using cellular
$P_{c,i}$	power level for idle state using cellular
$P_{sr,tx}$	power level for sending state using short range
$P_{sr,rx}$	power level for receiving state using short range
$P_{sr,i}$	power level for idle state using short range
$t_{c,rx}$	receiving time for the cellular link
$t_{c,i}$	idle time for the cellular link
$t_{sr,tx}$	sending time for the short range link
$t_{sr,rx}$	receiving time for the short range link
$t_{sr,i}$	idle time for the short range link
$E_{c,rx}$	energy level for receiving state using cellular
$E_{c,i}$	energy level for idle state using cellular
$E_{sr,tx}$	energy level for sending state using short range
$E_{sr,rx}$	energy level for receiving state using short range
$E_{sr,i}$	energy level for idle state using short range
E_{Coop}	overall energy level for cooperation
E_{noCoop}	overall energy level for no cooperation

3 Energy Measurements

As described in the last section a detailed investigation on the energy consumption for the individual actions and achievable data rates is needed. Therefore measurement results of the data rates and energy consumption for the cellular network and the short range network on the mobile device are presented shortly. A more detailed description of the measurement setup and results can be found in [6].

For the WLAN IEEE802.11 measurements, one N95 is used for sending broadcast packets of 1000 byte length towards ten other N95s distributed equidistantly between 3 m and 30 m. Several tests were conducted, where one test was sending five times 5.000 packets in a row as fast as possible with 10 sec pauses in between. In the active phase the sending and receiving power where measured and in the pause intervals the idle power was measured. For the energy measurements the energy profiler of Nokia were used [1]. While doing the WLAN measurements, the cellular connection was offline. The results of this measurement campaign is given in Table 2. The power levels for sending is larger than those of the receiving state. The receiving power levels for different distances between sender and receiver differ, which may be a reason that the mobile device with more distance to the sender is not receiving all packets and less energy is used in the signal processing part. The data rate is high with over five Mbit/s.

Table 2: Power Levels and Data Rate For WLAN Broadcast - 1000 byte

state	power value [W]	data rate [Mbps]
sending	$1,629$	$5,623$
receiving @ 3m	$1,375$	$5,379$
receiving @ 30m	$1,213$	$5,115$
idle @ 3m	$0,979$	–
idle @ 30m	$0,952$	–

The Bluetooth measurements were similar to that of the WLAN, but only between two N95 devices. The energy levels will not differ from unicast to broadcast transmission as only the recepient address will change. While doing the Bluetooth measurements, the cellular connection was offline. Table 3 is given the results for the Bluetooth measurements. The power levels are now quite low compared to WLAN, but the data rate is also smaller. Beneficial for the cooperation, as explained later on, is the low power level in idle mode.

The measurement setup for the cellular link was composed out of an Internet server transmitting UDP packets towards a Nokia N95 device over a 3G operator

Table 3: Power Levels and Data Rate For Bluetooth - 224 bytes / DM5

state	power value [W]	data rate [Mbps]
sending	$0,422$	$0,631$
receiving	$0,367$	$0,631$
idle	$0,161$	$-$

in Aalborg, Denmark. The results for the energy consumption for the receiving and the idle state are given in Table 4. As expected the mobile device will consume more energy in the receiving mode than in the idle mode. The receiving power level is even lower than the one used in WLAN. But as the data rate for the cellular link with 0.193Mbit/s is significantly lower than that of WLAN, the energy per bit ratio is worse for the cellular link.

Table 4: Power Levels and Data Rate For Cellular - 100 byte

state	power value [W]	data rate [Mbps]
receiving	$1,314$	$0,193$
idle	$0,661$	$-$

4 Cellular and IEEE802.11

In this section the energy consumption for cellular technology such as 3G for the overlay network and 802.11 technology for the short range exchange is calculated.

4.1 Streaming

For the streaming scenario it is assumed that the sub streams of the overlay network are conveyed in multicast channels. Those channels are sent out sequentially within one frame. A stand alone device would need to receive all substreams over the cellular link, while cooperative devices will share this task by receiving a subset of multicast channels and exchange the missing pieces over the short range link. As given in Figure 7 one cooperating mobile device is receiving one slot on the cellular link and will stay the rest of the frame idle. The received slot will be offered over the short range link in $1/(JZ)$ time. The $J-1$ missing slots will be received over the short range link as well in $(J-1)/(JZ)$ time. When the local exchange is over also the short range link is idle until the next frame starts. The cooperative energy consumption E_{Coop}^{stream} is given in Equation 5.

$$E_{Coop}^{stream} = \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(1-\frac{1}{J})}_{t_{c,i}} P_{c,i} + \underbrace{\frac{1}{J\cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J\cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(1-\frac{1}{Z})}_{t_{sr,i}} P_{sr,i} \tag{5}$$

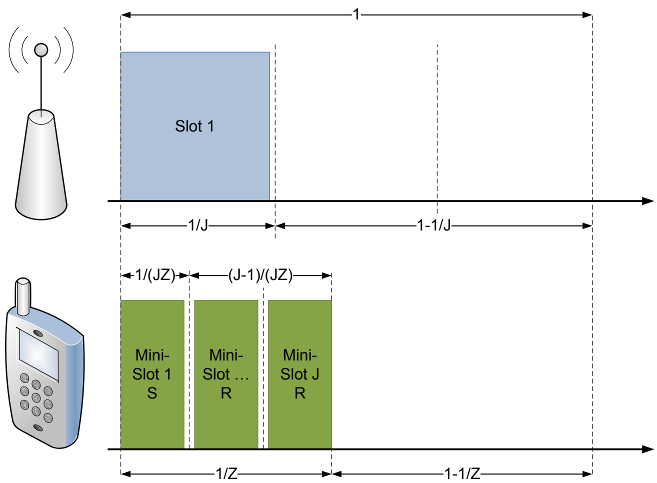

Figure 7: Streaming scenario for cooperative wireless network using Cellular and IEEE802.11 technology.

4.2 File Download

For the file download scenario it is assumed that all cooperating mobile devices have a dedicated cellular link receiving partial information that will be combined over the short range link. If $1/J \geq 1/Z$, as given in Figure 8, there will be no idle time at all on the cellular link but some idle time on the short range link. Figure 8 shows the case when the number of cooperating entities is small and the ratio Z is high. Equation 6 gives the energy consumption in the cooperative case for $1/J \geq 1/Z$.

$$E_{Coop}^{down} = \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{0}_{t_{c,i}} P_{c,i} + \underbrace{\frac{1}{J\cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J\cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{1}{J}-\frac{1}{Z})}_{t_{sr,i}} P_{sr,i} \tag{6}$$

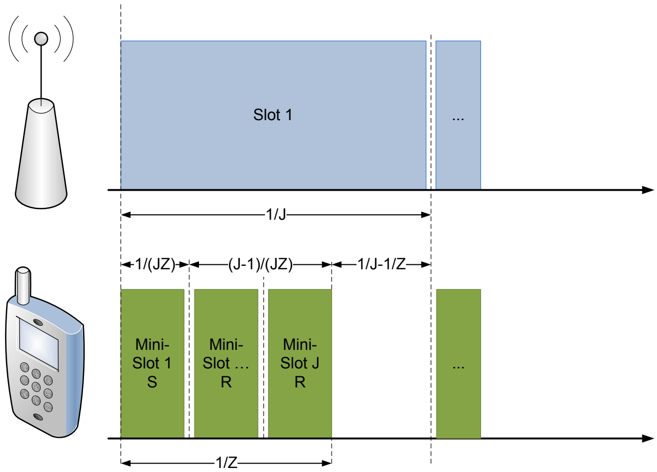

Figure 8: File download scenario for cooperative wireless network using Cellular and IEEE802.11 technology for $1/J \geq 1/Z$.

In Figure 9 the case $1/J < 1/Z$ is shown. Now there is no idle time on the short range link, but some remaining idle time on the cellular link. The energy consumption E_{Coop}^{down} for the cooperative case is given by Equation 7 if $1/J < 1/Z$.

$$E_{Coop}^{down} = \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(\frac{1}{Z} - \frac{1}{J})}_{t_{c,i}} P_{c,i} + \underbrace{\frac{1}{J \cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{0}_{t_{sr,i}} P_{sr,i} \quad (7)$$

5 Cellular and Bluetooth without Broadcast

As mentioned before in the architecture section, the energy consumption in Bluetooth for the master and the slave differs. Therefore a separated investigation of the master and the slaves is presented before deriving the mean value of it.

5.1 Streaming

As for the WLAN scenario, all mobile devices are receiving one slot over the cellular network, which is used for exchange over the short range technology. The master will then receive $J-1$ packets from its $J-1$ slaves as given in Figure 10 using the example of three cooperating mobile devices. The master

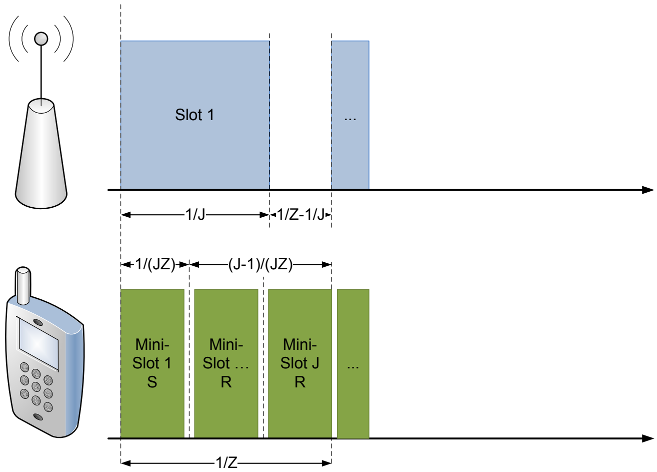

Figure 9: File download scenario for cooperative wireless network using Cellular and IEEE802.11 technology for $1/J < 1/Z$.

will send its own packet to $J-1$ slaves, while it will relay $J-2$ packets from other slaves to each individual slave. This will end up in $(J-1)^2$ transmissions for the master. A slave will send only one packet and receive $J-1$ packets from its master. The rest of the time the slave is idle. By subtracting the time needed to transmit and to receive from one frame time, the idle time is received. To calculate the t_{sr} values, the values of the master and slaves are weighted to build the mean value.

$$t_{sr,tx} = \frac{\frac{(J-1)^2}{JZ} + (J-1) \cdot \frac{1}{JZ}}{J} = \frac{J-1}{JZ} \tag{8}$$

The same is done for the idle time for the short range communication.

$$t_{sr,i} = \frac{0 + (J-1) \cdot \frac{JZ-1}{Z}}{J} = \frac{JZ-2J+2}{JZ} \tag{9}$$

All time values for the streaming scenario using Bluetooth without broadcast are given in Table 5.

As long as $(J-1)/Z$ is smaller than one or in other words, as along at the short range exchange fits into one frame, the energy consumption can be calculated by

Table 5: Streaming 3G/BTwoBr

Cellular	receive	$t_{c,rx}$	$1/J$
Cellular	idle	$t_{c,i}$	$1-1/J$
Master	send		$\frac{(J-1)^2}{JZ}$
Master	receive		$\frac{J-1}{JZ}$
Master	idle		$\frac{J(Z-J+1)}{JZ}$
Slave	send		$\frac{1}{JZ}$
Slave	receive		$\frac{J-1}{JZ}$
Slave	idle		$\frac{JZ-J}{JZ}$
Mean	send	$t_{sr,tx}$	$\frac{J-1}{JZ}$
Mean	receive	$t_{sr,rx}$	$\frac{J-1}{JZ}$
Mean	idle	$t_{sr,i}$	$\frac{JZ-2J+2}{JZ}$

$$
\begin{aligned}
E_{Coop}^{stream} = \; & \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(1-\frac{1}{J})}_{t_{c,i}} P_{c,i} + \\
& \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{JZ-2J+2}{J \cdot Z})}_{t_{sr,i}} P_{sr,i}.
\end{aligned} \tag{10}
$$

5.2 File Download

In case $1/J \geq (J-1)/Z$, there is no idle time on the cellular communication link ($t_{c,i} = 0$). The master and slave will act in the same way as in the streaming scenario, but the idle time are shorter now. The individual idle time can be calculated by subtracting the time for sending and receiving from $1/J$. To calculate $t_{sr,i}$, the mean of the values of the master and slaves is taken (see Equation 11). For $1/J \geq (J-1)/Z$ cooperative energy consumption E_{Coop}^{down} is given in Equation 12.

$$
t_{sr,i} = \frac{\frac{Z-J^2+J}{JZ} + (J-1) \cdot \frac{Z-J}{JZ}}{J} = \frac{Z-2J+2}{JZ} \tag{11}
$$

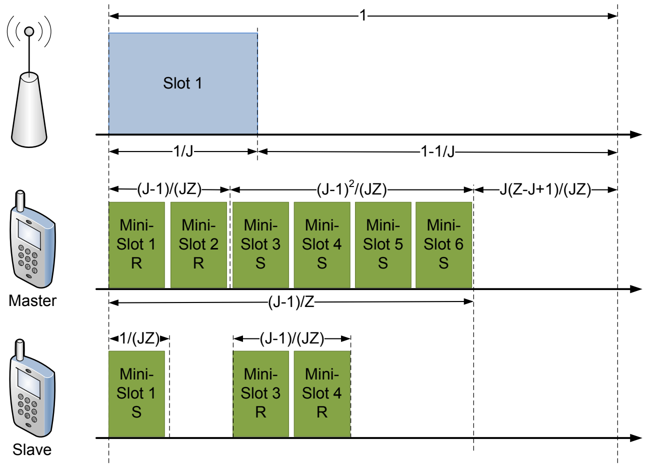

Figure 10: Streaming scenario for cooperative wireless network using Cellular and Bluetooth technology without broadcast functionality.

$$\begin{aligned} E_{Coop}^{down} = & \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(0)}_{t_{c,i}} P_{c,i} + \\ & \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{Z-2J+2}{J \cdot Z})}_{t_{sr,i}} P_{sr,i} \end{aligned} \tag{12}$$

In case the short range communication is not fast enough to exchange the data within the cooperative cluster $(1/J < (J-1)/Z)$, the Bluetooth master is creating idle time on the cellular technology and extending those of the slaves. The idle time of the cellular link equals $1/J$ subtracted from the time the Bluetooth master needs to send and receive packets. All time values for the different cases are given in Table 6.

$$t_{sr,i} = \frac{\frac{Z-J^2+J}{JZ} + (J-1) \cdot \frac{J-2}{JZ}}{J} = \frac{(J-1)(J-2)}{JZ} \tag{13}$$

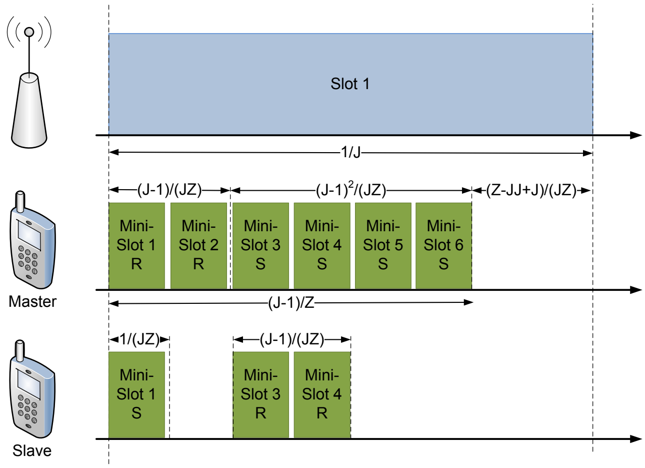

Figure 11: File download scenario for cooperative wireless network using Cellular and Bluetooth technology without broadcast functionality for $1/J \geq (J-1)/Z$.

$$E_{Down}^{down} = \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(\frac{J-1}{Z} - 1/J)}_{t_{c,i}} P_{c,i} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{(J-1)(J-2)}{J \cdot Z})}_{t_{sr,i}} P_{sr,i} \quad (14)$$

6 Cellular and Bluetooth with Broadcast

In contrast to the previous section, in this section it is assumed that the master in the Bluetooth piconet is able to broadcast packets to the slaves which is part of the Bluetooth standard but not implemented or accessible on all Bluetooth chip sets.

6.1 Streaming

Enabling the master to broadcast packets will result in a significant lower amount of packets that will be transmitted. The number of received packets by the master is not changed compared to the previous case. Also the number of received

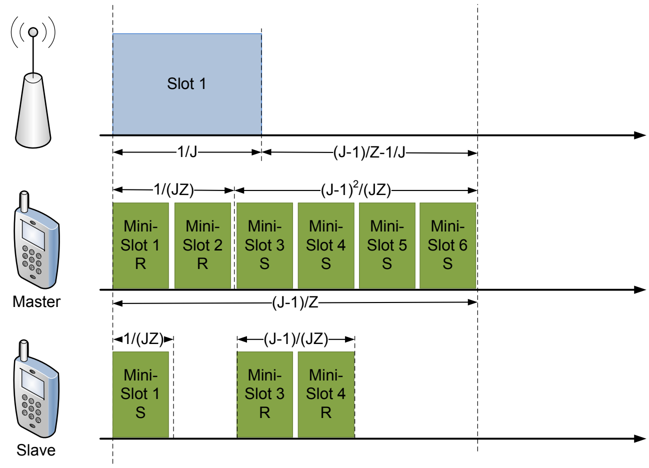

Figure 12: File download scenario for cooperative wireless network using Cellular and Bluetooth technology without broadcast functionality for $1/J < (J-1)/Z$.

Table 6: File Download 3G/BTwoBr

<table>
<tr><th></th><th></th><th></th><th>$1/J \geq (J-1)/Z$</th><th>$1/J < (J-1)/Z$</th></tr>
<tr><td rowspan="2">Cellular</td><td>receive</td><td>$t_{c,rx}$</td><td colspan="2">$1/J$</td></tr>
<tr><td>idle</td><td>$t_{c,i}$</td><td>0</td><td>$\frac{J-1}{Z} - 1/J$</td></tr>
<tr><td rowspan="3">Master</td><td>send</td><td></td><td colspan="2">$\frac{(J-1)^2}{JZ}$</td></tr>
<tr><td>receive</td><td></td><td colspan="2">$\frac{J-1}{JZ}$</td></tr>
<tr><td>idle</td><td></td><td>$\frac{Z-J^2+J}{JZ}$</td><td>0</td></tr>
<tr><td rowspan="3">Slave</td><td>send</td><td></td><td colspan="2">$\frac{1}{JZ}$</td></tr>
<tr><td>receive</td><td></td><td colspan="2">$\frac{J-1}{JZ}$</td></tr>
<tr><td>idle</td><td></td><td>$\frac{Z-J}{JZ}$</td><td>$\frac{J-2}{Z}$</td></tr>
<tr><td rowspan="3">Mean</td><td>send</td><td>$t_{sr,tx}$</td><td colspan="2">$\frac{J-1}{JZ}$</td></tr>
<tr><td>receive</td><td>$t_{sr,rx}$</td><td colspan="2">$\frac{J-1}{JZ}$</td></tr>
<tr><td>idle</td><td>$t_{sr,i}$</td><td>$\frac{Z-2J+2}{JZ}$</td><td>$\frac{(J-1)(J-2)}{JZ}$</td></tr>
</table>

and sent packets is the same for the slaves compared to the case where the Bluetooth master was not able to broadcast the messages.

In Figure 13 the activity plot for the streaming scenario is given. One mobile device is receiving one slot on the cellular and remains idle on this specific air interface for the rest of the frame. The Bluetooth master will receive $J-1$ packets from its $J-1$ slaves and broadcast those packets together with its own packet resulting in J transmissions for the master. For better illustration one master and two slaves are assumed in Figure 13. Any slave will send only one packet and receives $J-1$ packets over the broadcast channel from the master.

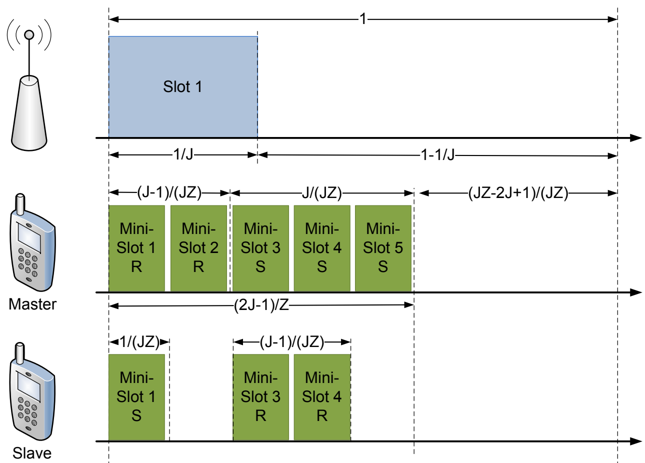

Figure 13: Streaming scenario for cooperative wireless network using Cellular and Bluetooth technology with broadcast functionality.

To calculate the idle time of the master, the time the master is receiving and sending is subtracted from the frame time.

$$t_{sr,i,master} = 1 - \frac{J}{JZ} - \frac{J-1}{JZ} = \frac{JZ-2J+1}{JZ} \tag{15}$$

But for $J = 2$, the idle time for the master needs to be rewritten as given in Equation 16.

$$t_{sr,i,master,J=2} = 1 - \frac{1}{JZ} - \frac{J-1}{JZ} = \frac{J(Z-1)}{JZ} \tag{16}$$

In Table 7 a general description of the idle time is given by using the variable α. For $J = 2$, α equals $1/J$ and 1 otherwise. This variable is used throughout the whole document. The same adjustment needs to be done for the mean sending time $t_{sr,tx}$. A slave will send only one packet and receive $J-1$ packets from its master. The rest of the time the slave is idle, such that $t_{sr,i,slave}$ equals

$$t_{sr,i,slave} = 1 - \frac{1}{JZ} - \frac{J-1}{JZ} = \frac{J(Z-1)}{JZ}. \tag{17}$$

Using $t_{sr,i,master}$ and $t_{sr,i,slave}$, the mean value $t_{sr,i}$ can be calculated. In Table 7 the values for the individual timing is given.

Table 7: Streaming 3G/BTwBr

Cellular	receive	$t_{c,rx}$	$1/J$
Cellular	idle	$t_{c,i}$	$1-1/J$
Master	send		$\frac{\alpha J}{JZ}$
Master	receive		$\frac{J-1}{JZ}$
Master	idle		$\frac{JZ-J-\alpha J+1}{JZ}$
Slave	send		$\frac{1}{JZ}$
Slave	receive		$\frac{J-1}{JZ}$
Slave	idle		$\frac{J(Z-1)}{JZ}$
Mean	send	$t_{sr,tx}$	$\frac{J+\alpha J-1}{J^2Z}$
Mean	receive	$t_{sr,rx}$	$\frac{J-1}{JZ}$
Mean	idle	$t_{sr,i}$	$\frac{J^2(Z-1)-\alpha J+1}{J^2Z}$

The energy spent for the *streaming* scenario is given in Equation 18.

$$\begin{aligned} E^{stream}_{Coop} &= \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(1-\frac{1}{J})}_{t_{c,i}} P_{c,i} + \\ &\underbrace{\frac{J+\alpha J-1}{J^2 \cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{J^2(Z-1)-\alpha J+1}{J^2 \cdot Z})}_{t_{sr,i}} P_{sr,i} \end{aligned} \tag{18}$$

6.2 File Download

The *file download* scenario is similar to the previous cases, only that the master is sending less packets than before.

In Figure 14 the case that the whole short range exchange can be done within one slot is depicted. For illustration reasons only three cooperating entities are assumed without loosing generality. The master will receive $J-1$ packets from the slaves and send J packet by himself using the broadcast capability. A slave on the other side is receiving $J-1$ packets and sends one packet towards the master. As the short range communication is fast enough the master has still some idle time (given in Table 8). The idle time of the slaves is even larger, resulting in the mean idle time for all mobile devices:

$$t_{sr,i} = \frac{\frac{Z-J-\alpha J+1}{JZ} + (J-1)\cdot\frac{Z-J}{JZ}}{J} = \frac{(JZ+1-\alpha J-J^2)}{J^2\cdot Z}. \tag{19}$$

The energy spent for this case is

$$E^{down}_{Coop} = \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(0)}_{t_{c,i}} P_{c,i} + \underbrace{\frac{J+\alpha J-1}{J^2\cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J\cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{JZ+1-\alpha J-J^2}{J^2\cdot Z})}_{t_{sr,i}} P_{sr,i}. \tag{20}$$

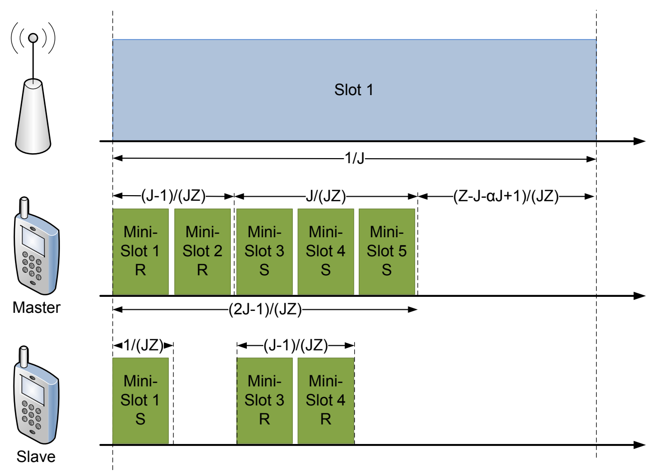

Figure 14: File download scenario for cooperative wireless network using Cellular and Bluetooth technology with broadcast functionality for $1/J \geq (2J-1)/(JZ)$.

If the short range exchange needs more time than the reception of one slot over the cellular link, the master has no idle time anymore, but is sending and receiving mini slots as given in Figure 15. On the other side the cellular link has now idle time that needs to be taken under consideration such that the overall energy consumption equals:

$$\begin{aligned} E_{Down}^{down} = \; & \underbrace{\frac{1}{J}}_{t_{c,rx}} P_{c,rx} + \underbrace{(\frac{2J-1}{JZ} - 1/J)}_{t_{c,i}} P_{c,i} + \\ & \underbrace{\frac{J+\alpha J-1}{J^2 \cdot Z}}_{t_{sr,tx}} P_{sr,tx} + \underbrace{\frac{J-1}{J \cdot Z}}_{t_{sr,rx}} P_{sr,rx} + \underbrace{(\frac{(J-1)^2}{J^2 \cdot Z})}_{t_{sr,i}} P_{sr,i}. \end{aligned} \tag{21}$$

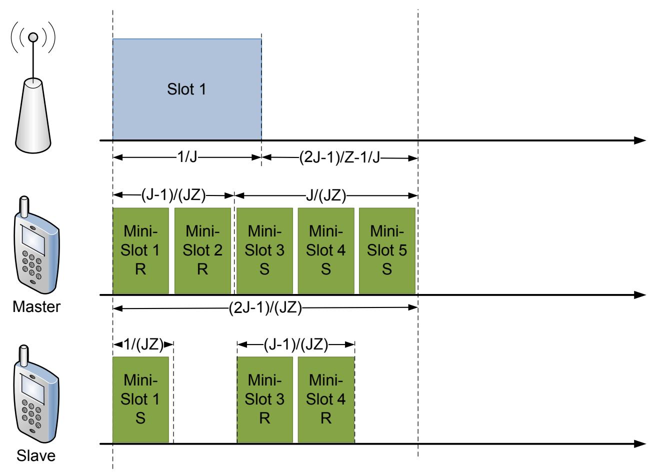

Figure 15: File download scenario for cooperative wireless network using Cellular and Bluetooth technology with broadcast functionality for $1/J < (2J-1)/(JZ)$.

In Table 8 the individual time values for the two cases $1/J \geq (2J-1)/(JZ)$ and $1/J < (2J-1)/(JZ)$ is given. The related energy calculation is given in Equation 20 and 21, respectively.

7 Results

Now the energy measurements of Section 3 and the analytical derivations of the energy consumption are combined to show potential benefits of cooperative wire-

Table 8: File Download 3G/BTwBr

			$1/J > (2J-1)/(JZ)$	$1/J < (2J-1)/(JZ)$
Cellular	receive	$t_{c,rx}$	$1/J$	
	idle	$t_{c,i}$	0	$\frac{2J-1}{Z} - 1/J$
Master	send		$\frac{\alpha J}{JZ}$	
	receive		$\frac{J-1}{JZ}$	
	idle		$\frac{(Z-J-\alpha \cdot J+1)}{JZ}$	0
Slave	send		$\frac{1}{JZ}$	
	receive		$\frac{J-1}{JZ}$	
	idle		$\frac{Z-J}{JZ}$	$\frac{J-1}{JZ}$
Mean	send	$t_{sr,tx}$	$\frac{J+\alpha J-1}{J^2 Z}$	
	receive	$t_{sr,rx}$	$\frac{J-1}{JZ}$	
	idle	$t_{sr,i}$	$\frac{JZ+1-\alpha J-J^2}{J^2 Z}$	$\frac{(J-1)^2}{J^2 Z}$

less networking in terms of energy saving and delay (latter one only for the file download scenario). Also the overall energy consumption is presented, to understand where most of the energy is consumed to improve the wireless technology. The result section is splitted up for the *streaming* and the *file download* scenario. The results are given for three different technology combinations, namely 3G/WLAN, 3G/BTwoBR, and 3G/BTwBR. Besides the energy consumption and savings, also the delay is given in this section. The delay D is calculated by

$$D = max(t_{sr,tx} + t_{sr,rx} + t_{sr,i}, t_{c,rx} + t_{c,i}). \tag{22}$$

7.1 File Download Results

First the file download results are presented. In Figure 16 the overall energy consumption is given for the three different cases. In Figure 17 the detailed energy consumption for the three different technology combinations are given. For each value of J, six columns are given. The first two are for the 3G/BTwBr case, while the left one is for the cellular energy consumption and the right one for the short range. The left column has always to parts, namely the receiving and the idle part. The right column has three parts with receiving, idle, and transmitting (from the bottom to the top). Column three and four are representing the 3G/BTwoBr case and the last columns are for the 3G/WLAN case. The overall energy consumption is the sum of both columns for a given case.

The 3G/WLAN case is using always less energy with each additional cooperating mobile device. For $J = 2$ the energy consumption is only a little bit smaller than the non cooperative case. As the non cooperative case has only one air interface powered up, in case of any cooperation the second air interface needs to be switched on. On top of that, for $J = 2$, each received packet has to be responded with a transmission of a packet on a short range link. This ratio becomes better for larger number of J.

In case Bluetooth is used instead of WLAN, the energy consumption for $J = 2$ becomes significantly better. For larger number of J, the Bluetooth with broadcast capabilities is using only a little bit less with each cooperating device. Bluetooth without broadcast capabilities is using more energy for a larger number of J. For the settings presented in the chapter, the energy consumption becomes even larger than the non cooperative case for $J > 5$. Now, the main energy consumption is taking place in the idle mode of the cellular air interface.

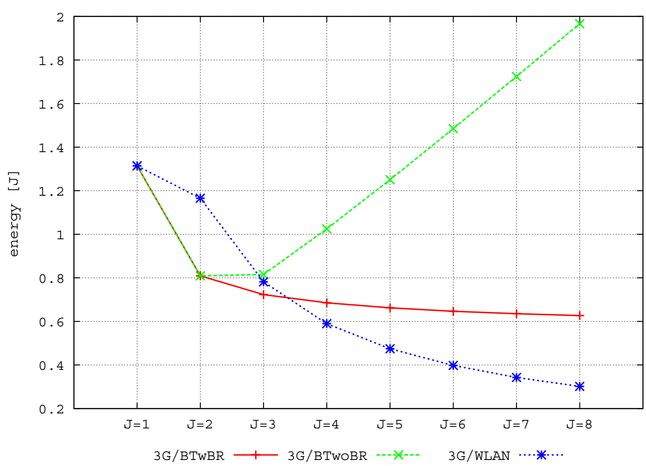

Figure 16: Overall energy consumption of three different cooperative technology combinations versus number of cooperating mobile devices for the *file download* scenario.

In Figure 18 the energy saving potential versus number of cooperating mobile devices for the *file download* scenario is given. As a reference the *ideal* energy

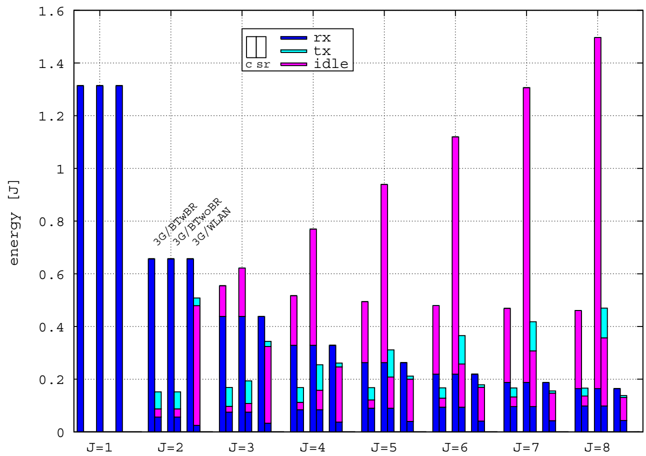

Figure 17: Detailed energy consumption of three different cooperative technology combinations versus number of cooperating mobile devices for the *file download* scenario.

saving curve is used, where it is assumed that no energy at all is consumed for the short range communication. The ideal energy savings can be calculated by $1 - 1/J$. The energy saving plot is a direct result of the energy plot. It can be seen that for $J \geq 4$, WLAN is giving the best energy saving results. Bluetooth with broadcast capabilities is giving good results for smaller number of J, but is saturating very quickly. The situation becomes worse for Bluetooth without broadcast capabilities. An energy saving can only be reported for $J < 6$. But already for $J \geq 3$ the gain is becoming smaller than for $J = 2$. Note, due to the larger coverage in WLAN, a larger number of J can be expected for WLAN than for Bluetooth.

Similar to the energy plot, the delay is presented in Figure 19. Here the each of the columns is representing the delay (they do not have to be added as in the energy case). Both columns are given to understand how long a certain air interface is staying in which mode.

The 3G/WLAN scenario is reducing the delay with each cooperating device. The delay in this case is $1/J$ as long as the data rate of the WLAN technology is significantly higher than the cellular network. For Bluetooth the data rate are smaller and due to their communication architecture the traffic they have to

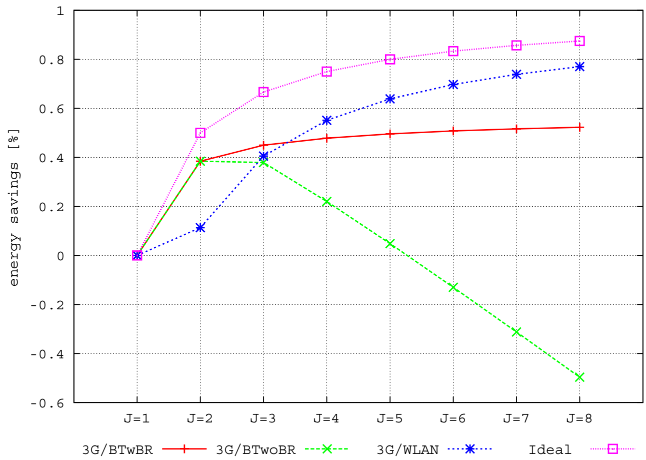

Figure 18: Energy saving potential versus number of cooperating mobile devices for the *file download* scenario.

support is much larger. For Bluetooth with broadcast capabilities, the delay is more or less stable over J resulting in a delay reduction to 50% for the specific values used in this example. The Bluetooth without broadcast capabilities is suffering by the large amount of data that has to be sent by the master. The master needs so much time that the cellular network interface is going into idle mode waiting for the short range to have finished the exchange. Also the Bluetooth slaves are most of the time in idle mode, such that most of the devices are spending their time, and as a result of that also their energy, in the idle mode. The only exception is the Bluetooth master, that is always receiving or transmitting on the short range without being idle on this particular air interface.

To sum up, for the *download file* scenario benefits for the energy consumption and the download delay can be expected for the 3G/WLAN and 3G/BTwBr. For 3G/BTwoBr a gain can only be achieved for a smaller number of cooperating mobile devices. Due to the large coverage of WLAN over Bluetooth, a larger number of cooperating devices can be assumed for that specific wireless technology. Note, the performance of the cooperative wireless networking can be improved significantly by lower power consumption in the idle mode. Other parameters such as data rate and power levels for sending and receiving have less impact.

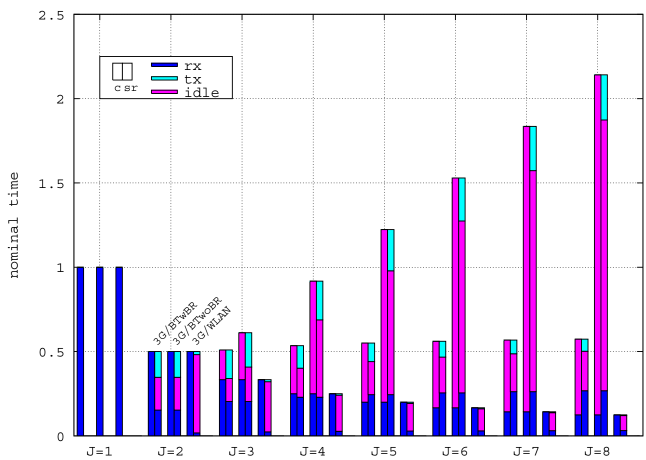

Figure 19: Delay of three different cooperative technology combinations versus number of cooperating mobile devices for the *file download* scenario.

7.2 Streaming Results

In this section the results for the *streaming* scenario are presented. In contrast to the *file download* scenario, where the heterogeneous air interface are switched off as soon as the disjoint data has been exchanged among the mobile devices, here both air interfaces are on all the time.

In Figure 20 and Figure 21 the energy consumption is given for the *streaming* scenario similar to Figure 16 and 16 for the *file download*, respectively. Obviously only the Bluetooth technology is using less energy than the non cooperative mobile devices. But the 3G/WLAN technology is using even more energy than the non cooperative mobile device. The reason is not the energy used in the activity phases, but the energy in the idle phases.

The energy consumption plot presented in Figure 20 leads to the energy saving plot in Figure 22. Here, Bluetooth without broadcast capabilities can only support four mobile devices as the data rate is not large enough to exchange the information over the short range fast enough.

In case the idle power of the WLAN technology could be reduced to zero, the 3G/WLAN combination would lead to an energy saving of 40% for $J = 8$. If further the idle time of the cellular would be zero (as for DVB-H), the energy saving would increase to 83%, which is only 4% below the *ideal case*.

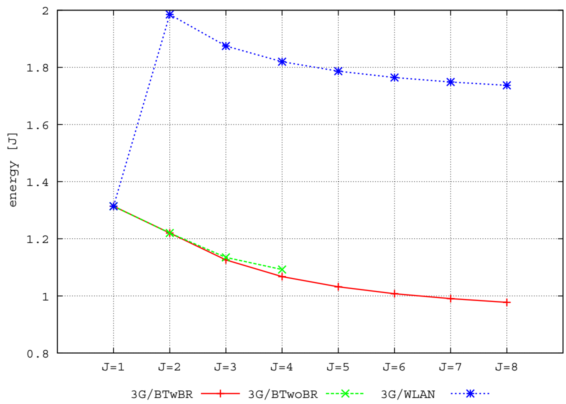

Figure 20: Overall energy consumption of three different cooperative technology combinations versus number of cooperating mobile devices for the *streaming* scenario.

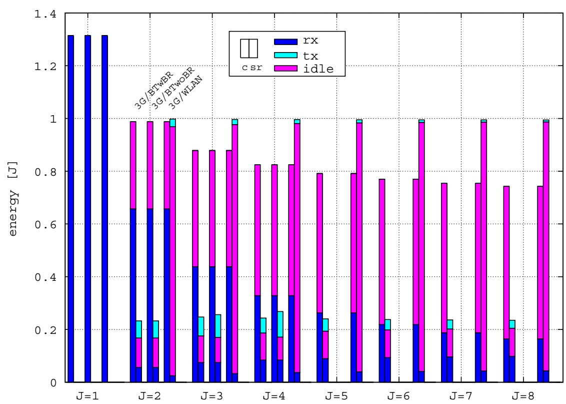

Figure 21: Detailed energy consumption of three different cooperative technology combinations versus number of cooperating mobile devices for the *streaming* scenario.

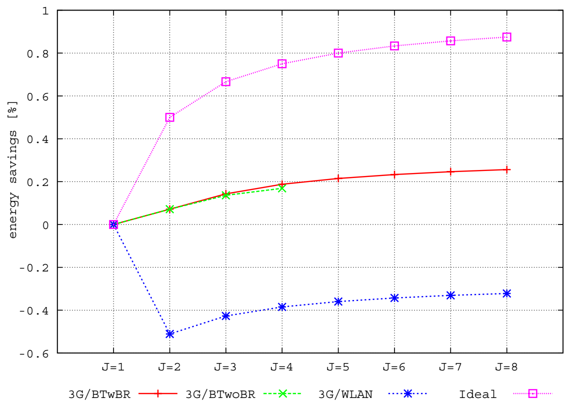

Figure 22: Energy saving potential versus number of cooperating mobile devices for the *streaming* scenario.

The delay plot in Figure 23 is giving the time values for the individual phases. The overall delay as such is obviously not improving as for the *file download*.

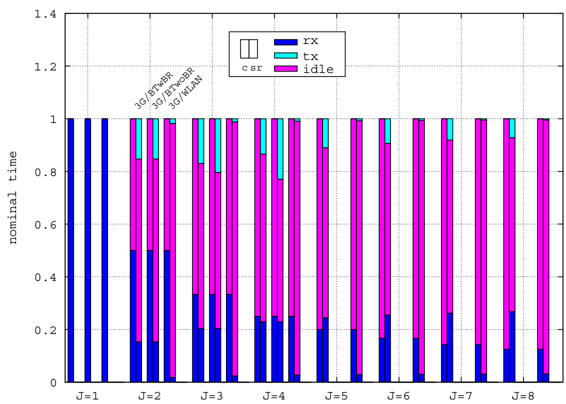

Figure 23: Delay of three different cooperative technology combinations versus number of cooperating mobile devices for the *streaming* scenario.

8 Conclusion

In this book chapter a new way to combine heterogeneous wireless technologies is advocated referred to as cooperative wireless networking. The main focus here was on the energy consumption and delay behavior for such an architecture. By means of measurements on commercially available mobile phones, the energy values and the data rates for different heterogeneous plots were presented. A large part of the chapter was reserved for the analytical derivation of the energy consumption of a cooperative wireless network compared to non cooperative state of the art ones. Potential gains for cooperative wireless networking were presented by using the measurement results in the analytical derivations.

For two different scenarios it was shown that cooperative wireless networking with existing heterogeneous wireless technologies, such as 3G, IEEE802.11, and Bluetooth, can already offer large energy savings and delay reducing for the *file download* scenario. For the second scenario, the *streaming* scenario, the gains were small in case of Bluetooth or not existent in case of WLAN. The reason lies in the scenario as such and the large power consumption in the idle phase in the cellular and the short range. As cellular systems already offer power consumption values near to zero for DVB-H, solutions have to be found for the short range technology using simply too much energy in the idle mode.

Acknowledgment

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Paper E

Cooperative Mobile Web Browsing

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Abstract

This paper advocates a novel approach for mobile web browsing based on cooperation among wireless devices within close proximity operating in a cellular environment. In the actual state-of-the-art, mobile phones can access the Web using different cellular technologies. However, the supported data rates are not sufficient to cope with the ever increasing traffic requirements resulting from advanced and rich content services. Extending the state-of-the-art, higher data rates can only be achieved by increasing complexity, cost and energy consumption of mobile phones. In contrast to the linear extension of current technology, we propose a novel disruptive architecture where mobile phones are grouped together in clusters, using a short-range communication such as Bluetooth, sharing and accumulating their cellular capacity. The accumulated data rate resulting from collaborative interactions over short-range links can then be used for cooperative mobile web browsing. By implementing the cooperative web browsing on commercial mobile phones, it will be shown that better performance is achieved in terms of increased data rate and therefore reduced access times, resulting in a significantly enhanced web browsing user experience on mobile phones.

1 Introduction and Motivation

One of the most rapidly growing sectors of the cellular phone market is the one corresponding to the mobile devices with advanced features. Today, these are represented typically by 3G (third generation) mobile phones. Services available on 3G phones are not limited only to voice or Short Message Service (SMS) but multimedia delivery and mobile web browsing are becoming equally important. The demand for accessing Internet-based services from mobile phones is growing strongly as there is a clear interest in checking emails, reading news and weather information, sharing pictures and videos, accessing social network communities on the go [14, 15]. Furthermore, the trend of developing mobile applications as web services will become more pronounced, aiming thus to achieve compatibility among mobile platforms. Therefore phone manufacturers have developed web browsers for mobile phones to give a full, desktop-like browsing experience to the users [12]. Even though Internet access from mobile phones is becoming popular all over the world, there are some issues that need to be addressed in order to attain such a widespread penetration of the wired Internet. We highlight the three following issues:

Prices Strategies for Web Services : Accessing Internet from a mobile phone is an expensive service today. Even though network operators promote new billing models for mobile data, such as flat rates, prices are still high.

Insufficient Data Rate Support : Compared to wired networks, mobile communications have some critical constraints, such as limited resources (small displays, battery, processing capabilities, etc.), and especially lower data rate support. For these reasons, the user experience of web browsing on mobile devices cannot be as good as on a desktop computer. One way of increasing the date rate is to implement new access technologies on the devices such as: Enhanced Data rates for GSM Evolution (EDGE), Universal Mobile Telecommunications System (UMTS), High Speed Downlink Packet Access (HSDPA) etc. However, the data rate on mobile phones is still low compared to wired networks. Future communication systems such as 4G technologies are promising much larger data rates, but accommodating higher data rates on mobile phones not only increase the complexity and price of the device but also its energy consumption.

Energy Efficiency : Even though energy could appear as the less obvious issue related to wireless web access, the energy consumption of mobile device is of key importance. In fact the energy consumption is directly related to the operating time of the mobile device, which in turn is already one of the most important issues for customers buying a new mobile handset. Mobile devices are battery driven and therefore limited in energy and power consumption. While the power limits are directly related to the heating of the mobile device, the energy limit is related to the operating time. As the mobile device is filled with several new features and high data rate wireless access, the stand by time will even decrease. Especially if we consider that the wireless communication capabilities of a modern mobile phone could require more than a half of the overall power consumption [8]. Aiming at tackling the aforementioned data rate and energy efficiency is-

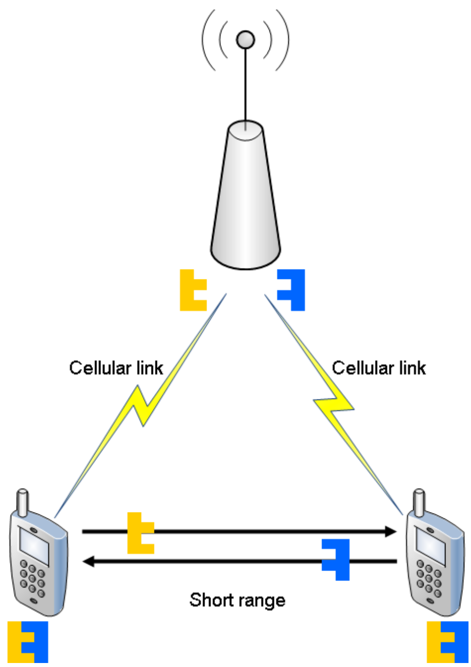

Figure 1: The Figure shows the cellular controlled peer-to-peer (CCP2P) architecture. The mobile phones in the cooperating cluster receive half of the content over the cellular link and exchange it over a short range link. By doing that they can get the full content.

sues, a recently proposed architecture, shown in the Fig. 1 and referred to as Cellular Controlled Peer-to-Peer (CCP2P), is advocated for web browsing [6, 7]. Authors in [11] have shown that wireless devices can benefit from cooperation in a *multicast scenario*. In that work it was shown that, if two or more mobile devices in proximity to each other are downloading the same content over the cellular link, they can decide to cooperate by forming a cluster over their short-range technology, e.g., Bluetooth. Each of them downloads just a portion of the original file over the cellular link and gets the rest from other mobile devices in the cluster over short-range links. The CCP2P approach assures higher data rates and less energy consumption for the mobile device. In this paper we extend the cooperative approach to web browsing. Web browsing takes place in an *unicast scenario* where each member of the cluster is interested in a different content. As illustrated in Fig. 6, mobile devices are clustered over short-range air interfaces and accumulate their cellular capacity in case pages are downloaded. Our aim here is to minimize the downloading time, enhancing the user experience. In our case, mobile phones can time-share their cellular link connection during the *page reading* phase in order to increase the virtual downlink data rate. The approach considered here is motivated by several measurement campaigns for web traffic. As underlined in [4, 10, 9] web traffic is cooperation-friendly. Each web page is composed out of multiple objects (figures, text, frames, etc.), each transported in a separate stream. The mean number of objects is 6.07, including the main HTML body with a mean size of 11 kB and five additional embedded objects with a mean size of 12 kB each [9]. This is similar to the work in [11], where a file can be split byte-wise for cooperative video streaming leading to some overhead due to the splitting. Those overheads are reported in [5].

Furthermore, the way the users access the web service makes it suitable for cooperation. Fig. 2 shows a sample web browsing session. Typically it consists out of one or more web page browsing cycles. Each cycle, starts with a short *web page request* (318 byte [9]) phase and it is followed by two further phases: the actual *page download* phase and the *page reading* phase:

- *web page request*: the web client retrieves information about the structure of the web content. The cellular air interface is used sporadically.
- *page download*: the web server conveys information towards the web client. The duration of this phase depends on the maximum data rate of the air interface (mean data is composed out of 12 kB main object and five embedded objects with 11 kB, altogether around 70kB) to be conveyed.
- *page reading*: after waiting the whole *web page request* and *web page download* phase, the content is ready to be displayed. Now the cellular air interface is idle. The user is now busy consuming the information out of the web page (mean duration 39.70 sec [9])

Due to this on-off behavior of the web traffic, there are times the cellular air interface is not used at all and other times the capacity of it is not sufficient. Thus, by cooperating mobile devices multiple on-off traffic source can be multiplexed statistically together. Cooperative wireless

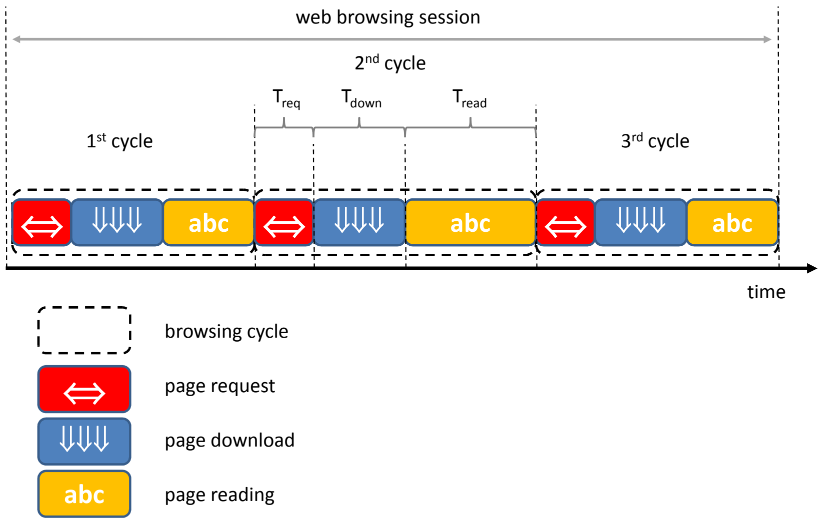

Figure 2: *Web browsing session*: it can consist of one or more web page browsing cycles. Each cycle consists of: a *Page Request* phase, a *Page Download* phase and a *Page Reading* phase. Usually the latter one lasts longer than the other two phases

Internet access (or web browsing) exploits the fact that several mobile devices, connected among themselves over short-range links and also to the servers (over cellular links), have uncorrelated access requirements.

2 Proposed Cooperative Web Browsing

Let us consider two mobile phones within short range coverage. Let us further suppose that both the mobile devices have dual connectivity capabilities, including a cellular air interface (e.g., GPRS, EDGE, UMTS, HSDPA, etc.) as well as a short-range communication air interface, such as Bluetooth. The choice of the short-range wireless technology, takes into account energy consumption and market penetration. Bluetooth has been chosen here because it is more efficient than IEEE802.11 WLAN in terms of energy consumption and it has the advantage of being already available in a large number of mobile phones. Whenever one mobile device wants to initiate a web browsing session, the two phones form a Bluetooth cluster where the first one acts as *master* and the other one as *slave*. The master downloads some parts of the webpage content (pictures, text, etc.), asking the slave to download the complementary parts, both using cellular links. As soon as one content has been downloaded, the data is sent to the master via Bluetooth. When all the contents have been collected, the web browser on the master device is able to recreate and to show the web page to the user. By cooperating in such a way, the so-called "virtual data rate" of the downloading phase is the sum of the data rates of the two mobile devices in the cluster. Taking into account that the time spent to send the last content via Bluetooth is small compared to the overall duration of the downloading phase, we can say that the speed of the downloading phase can be roughly doubled (more details in Section 5. However, the role of the master depends on which device wants to download the web page. For example, during a *page download* phase, initiated by one phone, it can happen that the cooperating mobile device makes also a request for a web page. This will cause an overlapping of requests. Therefore, two different scenarios are distinguished:

1. Only one mobile device at a time is within the *page download* phase.

2. Two *page download* phases are overlapping with each other.

Let us define the *virtual capacity* as:

$$C_{Vir} = C_{MD1} + C_{MD2}, \tag{1}$$

where C_{MD1} and C_{MD2} are the cellular link capacities that the master device and the slave device are dedicating to the cooperation respectively. A two-device cooperative scenario is illustrated in Fig. 3, showing the different values for C_{Vir} in both the cooperative and non-cooperative case without overlapping of the download phases. In case of cooperation, the time needed for the page download is shorter since the C_{Vir} is higher and the gain achieved by cooperating is shown in the same picture.
In the second scenario, the *page download* phases overlap for some time. In such a situation, each mobile device is acting selfishly and downloading its own contents (see Fig. 4) first. However, when the mobile becomes idle again and not being in its own *page download* phase, the slave offers its cellular link for the cooperation. This means that the C_{Vir} is increased only when the *page download* phases are not overlapping. Therefore, in this scenario, the gain highly depends on the duration of the overlapping and it is smaller, compared to the one in the previous case. Note that for illustrative purposes we assumed that the *page request* phase cannot be done in a cooperative way, and the air interface should

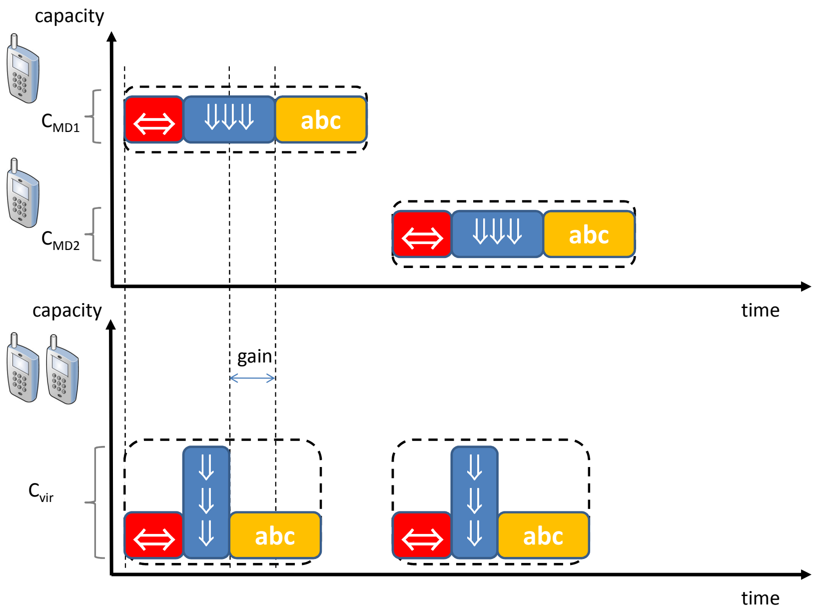

Figure 3: The Figure shows the values of C_{Vir} in the cooperative as well as non-cooperative case without overlapping of the download phases

be used exclusively for each mobile device in this given phase, which can be assumed to be rather small. We can distinguish 4 different behaviors of the terminals doing web browsing:

- *Standalone behavior*: each device is performing the web browsing without cooperation. In this case, the nominal downloading time is equal to 1.
- *Altruistic behavior*: each device is sharing its cellular link even if it is not interested in web browsing. In this case, neglecting the *page request* phase due to the small amount of data, J mobile devices could cooperate over the accumulated air interfaces reducing the download time to $1/J$ if the download activities would be scheduled in a perfect way.
- *Non altruistic behavior with perfect synchronization*: each device is cooperating only if it is interested in web browsing; there is no overlapping of download phase due to a perfect synchronization.

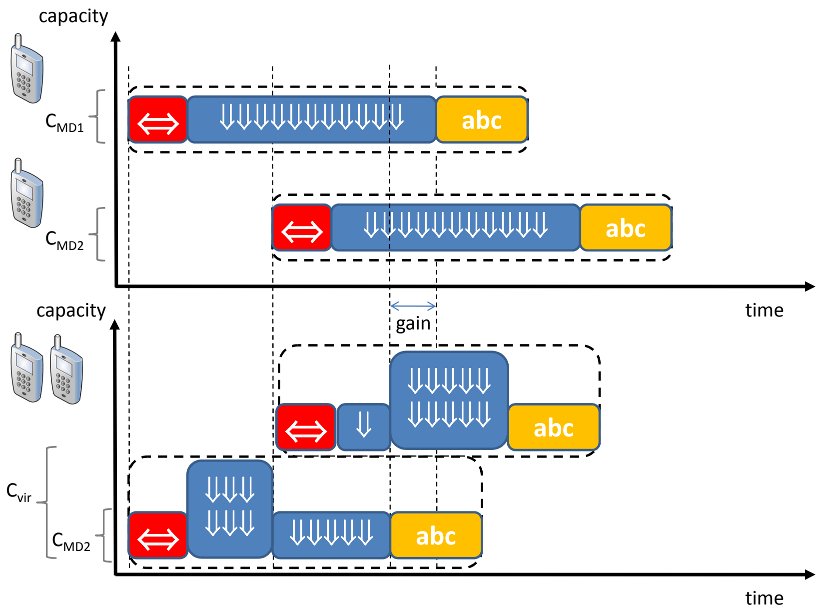

Figure 4: *Overlapping Page Download Phases*: the Figure shows the virtual capacity in the cooperative and non cooperative web browsing when the *page download* phase on the two devices are overlapping with each other. The virtual capacity is increased only when the *page download* phase of the two devices are not overlapping. Comparing this Figure with the Fig. 3, you can see that the gain in the cycle duration is smaller due to the fact that the devices are not cooperating all the time.

- *Real case*: each device is cooperating and overlapping of download phases are possible, therefore the time to download in a cooperative manner will be slightly larger, as all cooperating mobile devices are statistically multiplexed on the virtual capacity.

3 Technical Description of the System

We have implemented the newly introduced system architecture on commercial phones using Python for S60 [16, 17] to evaluate its performance. The application is installed on both master and slave phones. When the web browsing session starts, a Bluetooth connection is established between them, in order to form the cooperation cluster. The master sends a request for the header of the specified web page to the web server and the *page request* phase starts. After receiving this request, the web server replies to the phone by sending all the information about the requested page. Now the *page download* phase starts. We can divide this phase into two sub-phases: *Web Page Processing Phase* and *Components Downloading Phase*.

3.1 Web Page Processing Phase

During this phase, the information retrieved during the *Web Page Request Phase* are processed by the master performing the following actions:

- The content of the URL is processed.
- A searching process starts looking for a logical predefined pattern in the content of the URL. These patterns represent the paths of all external components in the web page, such as pictures and external links.
- The header of each component is retrieved and put into a list.
- The entries are classified according to their component type, such as an image, an anchor, an external link or an internal link.
- The list is split in two sub-lists equally balanced (if possible), based on the component sizes (see Fig. 5) if known. Note that the splitting of the web content into objects is done with nearly no overhead.

At the end of this phase, the master phone has two sub-lists containing the links of components. This information is now used to download components during the next phase.

3.2 Components Downloading Phase

When the *Web Page Processing Phase* is over, the actual download of the components can start:

- The master phone sends one of the two sub-lists of the components to the slave.
- The two phones start to download components according to the sub-list.
- Both files, the one downloaded by the master and the one downloaded and transferred by the slave, are stored in a folder on the memory of the master phone.

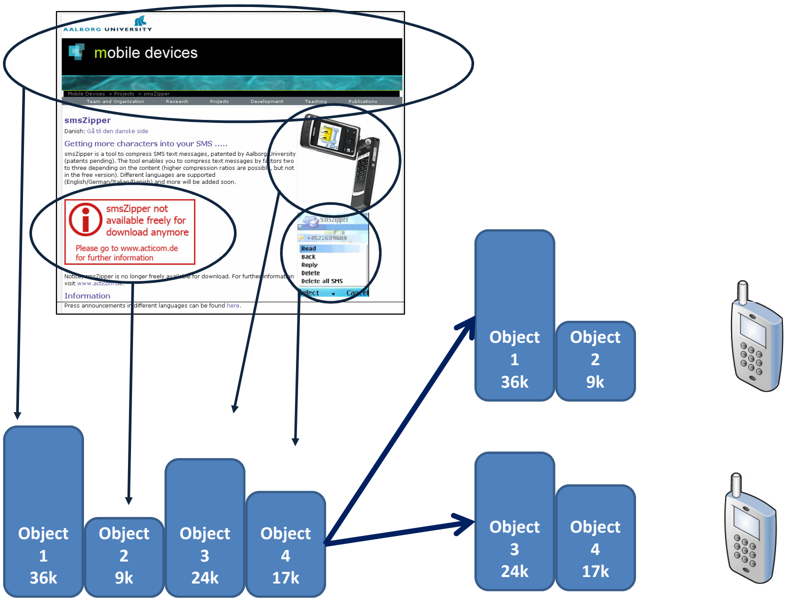

Figure 5: *Web Page Processing Phase*: this Figure shows how the content of the web page is processed. All the components are classified and inserted into a list. The list is split into two sub-lists in such a way that the size of them is as much balanced as possible.

- As soon as all the contents are downloaded, the web browser builds up the page and shows it to the user.

As discussed before, this is the most critical phase. In fact, if the slave requests another web page at this point, the cooperation stops. In this case, the slave sends to the master phone three pieces of information:

1. a sub-list containing the remaining components to be downloaded.
2. the contents eventually downloaded already
3. a request of cooperation as soon as the master ends its own *Downloading Phase*

Now the *Downloading Phases* are overlapping and both the master and the slave proceed the download without cooperation. The overall system can be improved

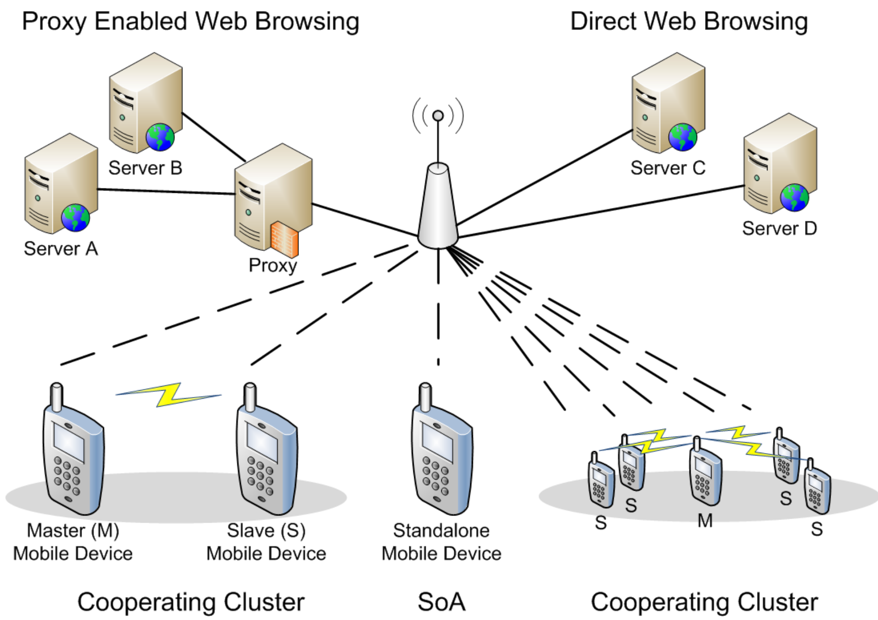

Figure 6: Architecture for non-cooperative and cooperative web browsing with direct or proxy enabled Internet access.

by adding a proxy server working as an intermediate processing unit between the master phone and the web server (see Fig. 6). This approach is referred to as *Proxy Enabled Web Browsing*. The master phone sends the header request of the specified web page to the proxy instead of sending it directly to the web server. Upon receiving the request, the proxy establishes a TCP connection to the web server forwarding the request for the header. The proxy is now in charge of the *Web Page Processing Phase*. When this is over, the *Web Page Components Downloading Phase* starts. In this second approach, the proxy does the job that previously was done by the master phone in the *Web Page Processing Phase*.

4 Discussion

The presented work shows the feasibility of cooperative mobile web browsing among wireless devices. Even though these initial results are encouraging, there are several additional issues that need to be addressed to fully understand the considered cooperative web browsing approach. Next, we discuss some important issues that need to be investigated in more detail.

4.1 Incentives for Cooperation

Even though cooperation is technically feasible, the question is whether users may be willing to cooperate. As given in [2, 7, 6] two basic elements enabling cooperation are *reciprocity* and *means for detection of cheaters*. In the case considered here, we need to ensure that mobile devices contributing to a cooperative cluster in terms of energy also get some benefits. In other words, the return of investments has to be quick and reliable, in order to motivate users to join a cooperative cluster. Therefore, basic rules such as Tit for Tat [2] should be applied. In the case of two cooperating entities that are totally unknown to each other, a basic trust level needs to be established. For instance, after agreeing to cooperate, mobile devices allow to each other to use 140 kB over the cooperative link, which corresponds approximately to two web requests according to the model developed in [9]. In case one mobile device has exploited this trust level without contributing to the cluster, it may not get anymore cooperative support unless the other one starts obtaining some benefits. Once the two mobile devices have already exchanged some data, the trust level may increase over time. The initial trust level highly depends on the pricing policy, e.g., flat rates or transported information (pay per bit).

4.2 Security and Privacy

As wireless devices share directly parts of their information, security and privacy become key issues. First, privacy needs to be assured as in a wireless scenario all information can be sniffed by potential intruders. More importantly for our proposed scenario is the legal issue in case some of the cooperating entities would access and share not legal content. Clearly, the network has to ensure the identification and storage of the final destination of the packets.

4.3 Number of Cooperating Mobile Devices

Whether cooperative web browsing can be used depends highly on the number of short-range communications enabled devices (e.g., Bluetooth) nearby the initial user willing to cooperate. A large number of cooperating mobile devices would be beneficial to find always *ideal* cooperating partners and to reduce the download time even more. On the other hand, some users tend to switch Bluetooth off to extend the battery lifetime and to reduce the risk of malware attacks. Authors in [13] present the results of a measurement campaign aimed at better understanding of the number of potentially cooperating mobile devices in different scenarios. More precisely, measurements show the number of wireless devices like mobile phones, with Bluetooth activated operating in public places (airports, bars, shopping malls, etc). Depending on the specific location an average of five to ten mobile devices have activated Bluetooth. In some scenarios it was found that there could be more than 50 Bluetooth capable mobile devices. Furthermore, we are witnessing the first commercial products creating strong direct links between users of mobile devices over the short-range links, such as the Microsoft's Zune devices.

4.4 User Friendliness

In order to be successful, the cooperative mobile web browsing has to be totally transparent to the user. Users would be annoyed or not even technically capable taking care of the mobile device discovery and cluster forming.

5 Results

We have used the developed application to evaluate the performance of the cooperative web browsing in terms of energy, time and data rate achieved. Each test we have run, consist in downloading one webpage with six components (images) for a total amount of data equal to 70 kB as suggested by [9] and discussed in Section 1. To simulate a real case where a user downloads several pages during a web browsing session, tests have been repeated many times varying the number of cycles from one to four (see Fig 2) in both cooperative with no overlap and non cooperative scenarios. The assumption that we have no overlap is motivated by the Bluetooth measurements campaign conducted in [13]. As mentioned in Section 4.3, authors found that there would always be several cooperative entities available around and even though some of them mobile devices could be downloading at the same time of a request, chances to find at least one partner entity that is free, are very high. Therefore, let us assume for the cooperative scenario with no overlap to have two phones (we have used Nokia N95s [1]) running our application and we assume that they know the Bluetooth address of each other to avoid the Bluetooth device discovery procedure. In this case the phone requesting the webpage, downloads half of the total amount of data (D_{tot}) from the cellular link and, upon establishing a connection, receives the other half via Bluetooth from the cooperating phone. In each test we have measured the following:

- Time for downloading the page
- Average power level
- Data rate for both cellular and Bluetooth communication
- Time to setup the Bluetooth connection

Table 1: Mean values for $T_{BTsetup}$ and DR_{BT}.

Time BT setup [s]	**BT data rate[kbps]**
0.175	1000

In the cooperative scenario we define the time needed to download the page, T_C as:

$$T_C = \max(T_{BT}, T_{Cell}), \tag{2}$$

where T_{BT} is defined as:

$$T_{BT} = \frac{1}{2} \cdot \frac{D_{tot}}{DR_{BT}} + T_{BTsetup}, \tag{3}$$

is the time needed for Bluetooth to setup the connection ($T_{BTsetup}$) and receive the requested components. DR_{BT} is the datarate achieved by the Bluetooth connection when receiving data. Furthermore we define the time needed to download components over the cellular link as:

$$T_{Cell} = \frac{1}{2} \cdot \frac{D_{tot}}{DR_{Cell}}, \tag{4}$$

where DR_{Cell} is the datarate achieved when downloading data using the cellular link.
In the non cooperative scenario we define the time needed to download the entire data using only the cellular link, T_{NC} as:

$$T_{NC} = \frac{D_{tot}}{DR_{Cell}}. \tag{5}$$

To compare the performance of the system in terms of time, we introduce T_{ratio} defined as:

$$T_{ratio} = \frac{T_C}{T_{NC}} = \begin{cases} \frac{1}{2}, & T_{Cell} > T_{BT} \\ \frac{1}{2} \cdot \frac{DR_{Cell}}{DR_{BT}} + \frac{T_{BTsetup} \cdot DR_{Cell}}{D_{tot}}, & T_{Cell} < T_{BT} \end{cases}. \tag{6}$$

Mean values for $T_{BTsetup}$ and DR_{BT} obtained during the tests are shown in Table 1.

T_{ratio} represents the percentage of time needed in the cooperative scenario normalized to the one needed in the non cooperative one. Figure 7 shows values of T_{ratio} plotted against DR_{Cell} for different sizes of D_{tot}.

Similarly, in Equation 7 we define a datarate ratio, DR_{ratio}, to compare the

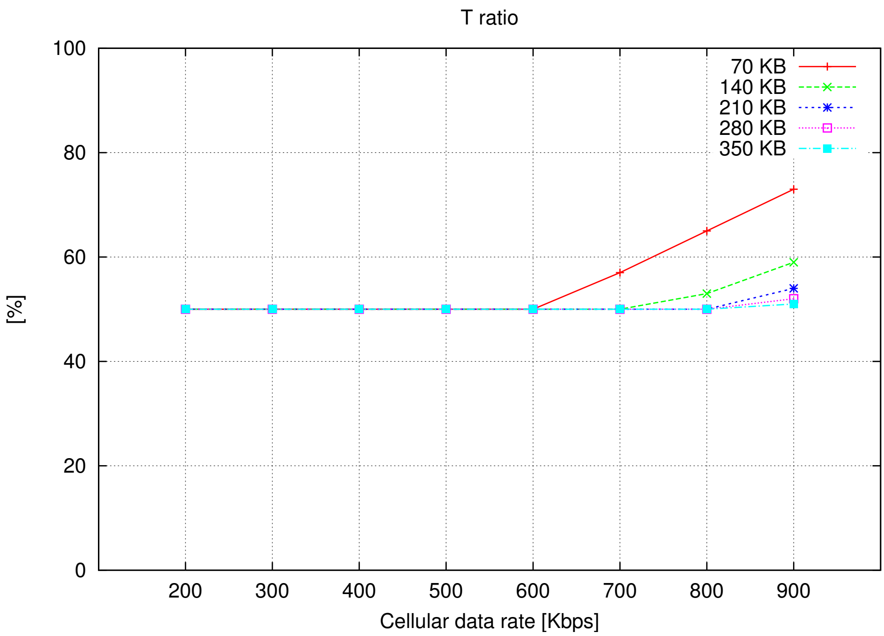

Figure 7: T_{ratio} plotted against DR_{Cell} for different sizes of D_{tot}.

performance of the system in terms of datarate. Results are shown in Figure 8 where D_{ratio} plotted against DR_{Cell} for different sizes of D_{tot}.

$$DR_{ratio} = \frac{DR_C}{DR_{NC}} = \frac{\frac{D_{tot}}{T_C}}{\frac{D_{tot}}{T_{NC}}} = \frac{T_{NC}}{T_C} \tag{7}$$

In order to measure the energy spent during the cooperative web browsing we have to quantify levels of power consumption. For doing that we used the in-built Nokia energy profiler [3] running on the phones. The energy profiler is an application that allows to make measurements without any additional hardware. It logs, for example, values for power consumption with a sample rate of 250ms. However, to check the correctness of the data given by the energy profiler on the phone, the complete setup includes the AGILENT 66319D used as multimeter. It is connected to a PC which is running the Agilent 14565B device characterization software, a tool designed for evaluation of portable battery powered device current profiles.

By defining the energy spent in the non cooperative case as:

$$E_{NC} = T_{NC} \cdot P_{NC}, \tag{8}$$

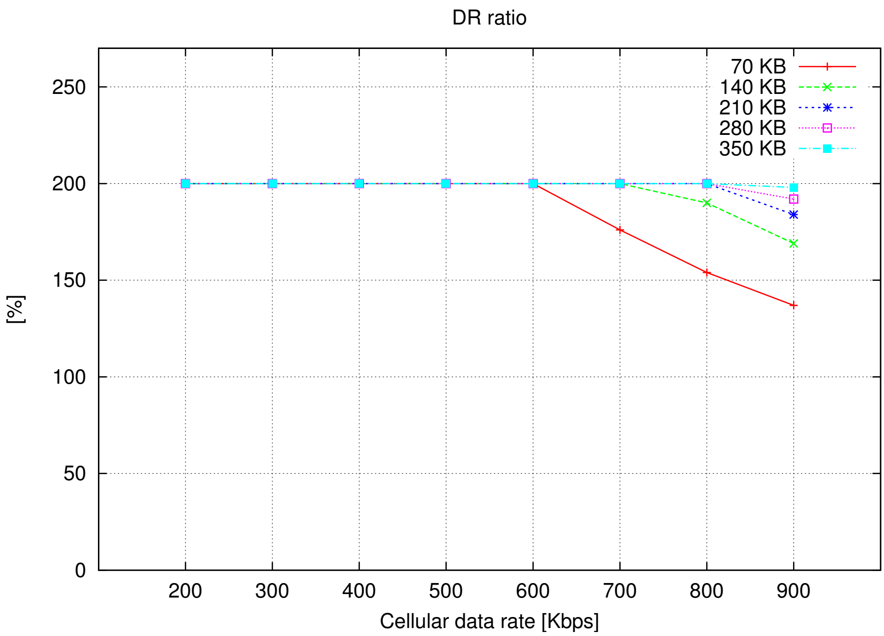

Figure 8: D_{ratio} plotted against DR_{Cell} for different sizes of D_{tot}.

and the energy spent by the phone requesting the page in the cooperative scenario as:

$$E_C = T_C \cdot P_C, \tag{9}$$

we can calculate the energy ratio $E_{ratio,single}$ for the single phone as:

$$E_{ratio,single} = \frac{E_C}{E_{NC}} = \frac{T_C}{T_{NC}} \cdot \frac{P_C}{P_{NC}}. \tag{10}$$

Although, for a fair comparison, for the cooperative case we will consider the energy spent by both the phones. Results of measurements on power levels of both the phones during the cooperative web browsing have shown that there is not a significant difference while downloading data using the cellular link and receiving or sending data with Bluetooth. Therefore we assume that the energy consumption for the entire system in case of cooperation is twice the energy spent by the master phone. Therefore we can define the energy ratio of the overall system, $E_{ratio,system}$ as:

$$E_{ratio,system} = \frac{2 \cdot E_C}{E_{NC}} = 2 \cdot \frac{T_C}{T_{NC}} \cdot \frac{P_C}{P_{NC}} \tag{11}$$

Figure 9 shows values of $E_{ratio,system}$ plotted against DR_{Cell} for different sizes of D_{tot}. In terms of downloading time, and therefore datarate, results show that

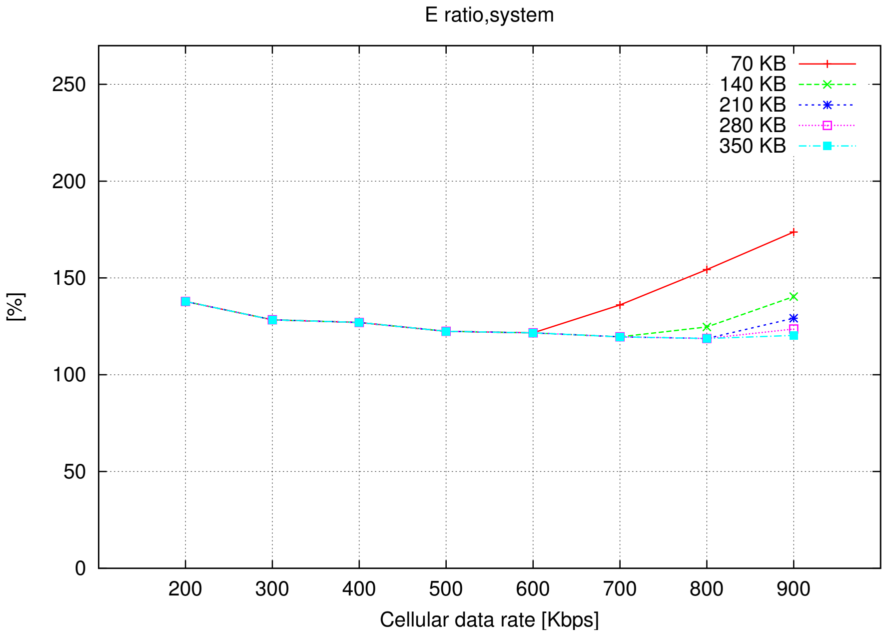

Figure 9: $E_{ratio,system}$ plotted against DR_{Cell} for different sizes of D_{tot}.

the cooperative webbrowsing approach outperforms the standard approach. In fact the first approach is always twice faster than the latter one as long as T_{Cell} is greater than T_{BT}. When T_{Cell} becomes smaller than T_{BT}, performance degrades due to $\frac{DR_{Cell}}{D_{tot}}$ in Equation 6. On the other hand, in contrast to the cooperative scenarios described in [19, 18, 11], cooperative web browsing is not leading directly to energy savings. In fact the performance in terms of energy of the overall system is worse if compared to the non cooperative case and it starts to degrade even more when $T_{Cell} < T_{BT}$. Nevertheless, if the quality of the service achieved by the cooperative web browsing wants to be achieved with a standalone phone the price to pay in terms of energy and complexity will be much higher. In Fig. 10 the quantitative energy consumption over the download time is given for one standalone mobile device, different number of cooperating mobile devices, and future mobile devices as foreseen in 4G. The standalone mobile device exhibits the lowest energy consumption with the largest download time. By cooperation the download time can be reduced (ideally inversely proportional to the number of cooperating mobile devices), but also a slight overhead in energy caused by the short range technology has to be paid. Note that this overhead is rather small compared to the energy requirement of the cellular air interface, and more importantly, it is nearly independent from the number of cooperating entities. If cooperation is not an option, future mobile devices will offer also larger data rates, but at the expense of dramatically higher energy consumption.

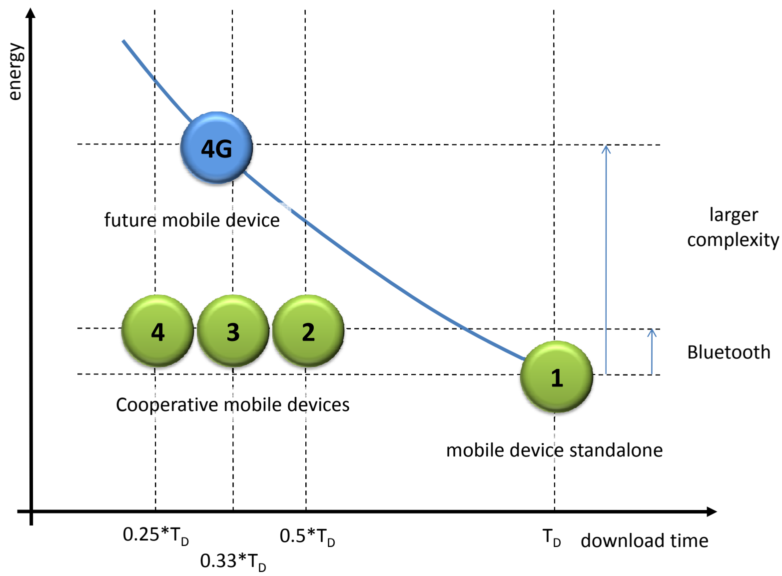

Figure 10: Energy consumption for a state of the art stand alone mobile device, cooperative mobile devices of the same class, and future mobile devices referred to as 4G.

6 Conclusion and Outlook

In this paper, we have proposed a novel approach for web browsing on mobile phones exploiting cooperation, allowing cooperative users to download their web content faster than standard non-cooperative mobile devices. We are motivated by the fact that web browsing applications are becoming increasingly important for mobile devices. This is not only driven by the users' need to be connected to Internet on the go, but also by the fact that future mobile applications will be realized as web applications to ensure mass compatibility.

In this work we have highlighted the fact that standard mobile devices provide often enough insufficient user experience due to the low supported data rate. Future mobile devices targeting higher data rate may be seriously limited by energy constraints. Therefore a cooperative approach among mobile devices has been introduced and a cooperative application for mobile phones has been implemented for evaluating the performance of the proposed system. Results show that cooperative web browsing by two mobile devices can increase the virtual capacity of the cellular link and can thereby reduce the duration of the downloading time. Even better performance could be achieved by more cooperative mobile devices. Therefore this new architecture can be used to overcome the problem of low data rates for Internet access on mobile phones. On the other hand we have shown that energy consumption increases when using the cooperative web browsing. Nevertheless, to achieve the same performance in terms of datarate, a non cooperating standalone mobile phone would pay an higher price in terms of complexity and energy. In our future work we will focus on stimulating cooperation looking more into trust level concepts introduced in Section 4 and also the robustness of the cooperation should be investigated. In case the cooperative cluster will fall apart, while downloading in a cooperative manner, the splitting of the objects is more important. So far the splitting is done by the object size only. But in the future this can be done in a different and more robust way, even though it will be a trade off with some longer download times.

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